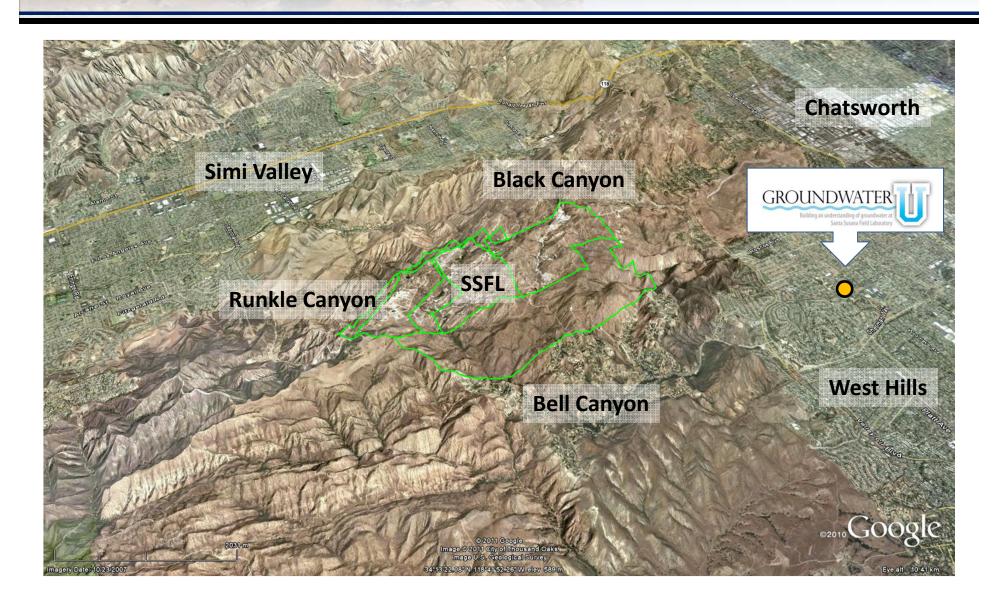


Session Outline

- Site Operations and Contaminants
- TCE Nature and Extent
- Contaminant Transport Processes
- Role of Diffusion
- Computer Representation of Plumes

Upland Site Between Communities

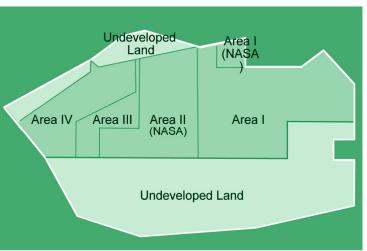


Areas of Operation at SSFL

Overall Property is 2,850 acres

3 miles x 1.5 miles





Boeing-owned:

Area I 670 acres

Area III 114 acres

Area IV 290 acres; DOE-leased 90 acres

Undeveloped Land - Boeing-owned 1,325 acres

NASA-administered:

Area I: ~50 acres

Area II: 400 acres

Two Primary Functions at SSFL



Rocket Engine Testing for NASA

- 1949-2006
- Six Test Stands 17,000 Rocket Engine
 & Component Tests
- Last test March 3, 2006

Nuclear Research & Liquid Metal Research for DOE

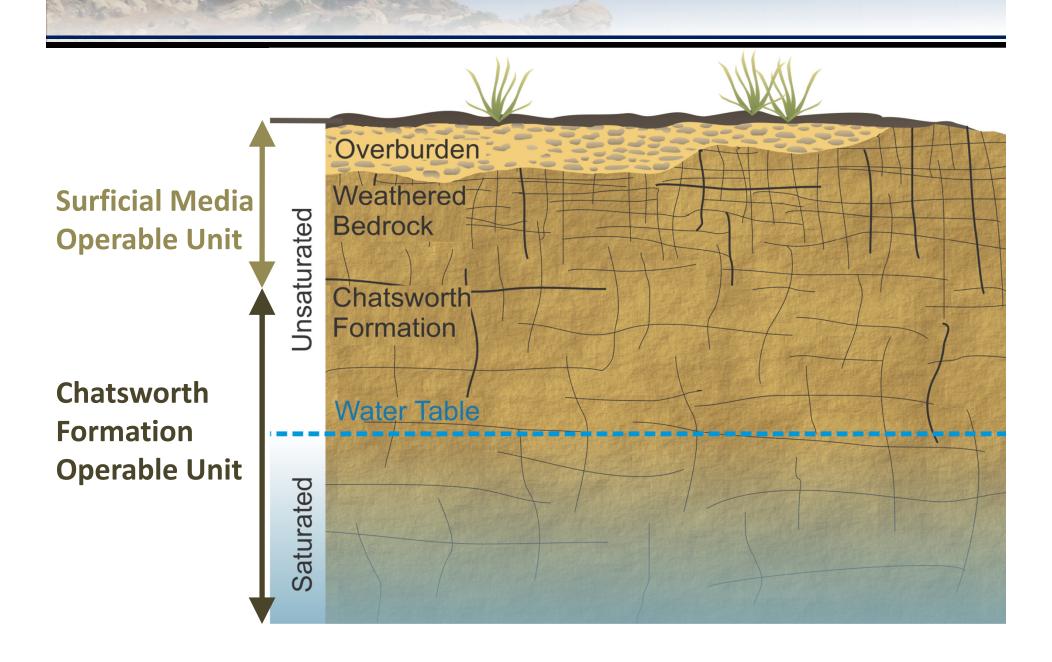
- Nuclear Power Research: 1956-1983
- Ten reactors
- Sodium component test facilities
- DOE Program ends 1988



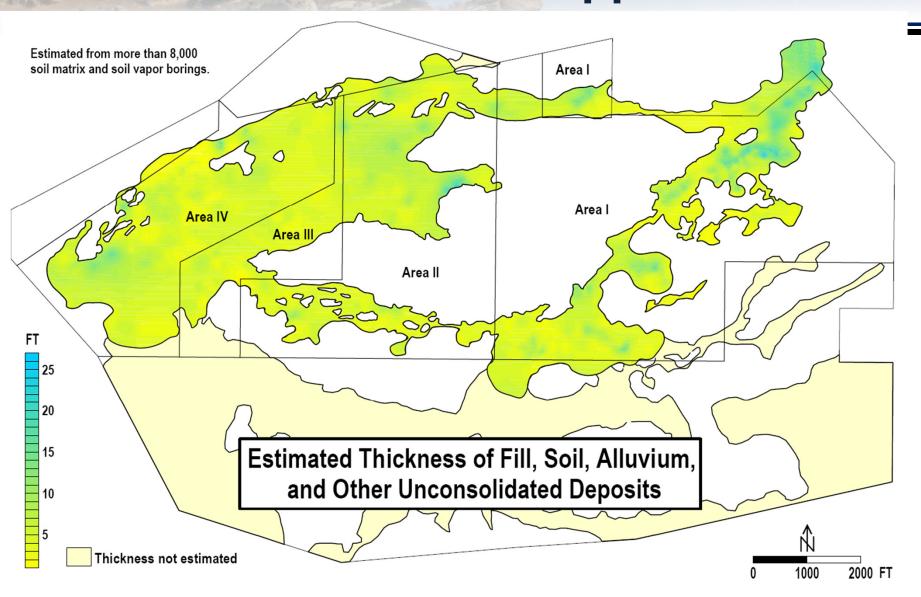
Environmental Investigations

- Contaminants found on-site: solvents, metals, perchlorate, petroleum hydrocarbons, mercury, dioxin, furans
- Surface water, soil, bedrock, groundwater:
 all being addressed in separate programs
- Monitored surface water outfalls surround site

Two Subsurface Investigation Programs

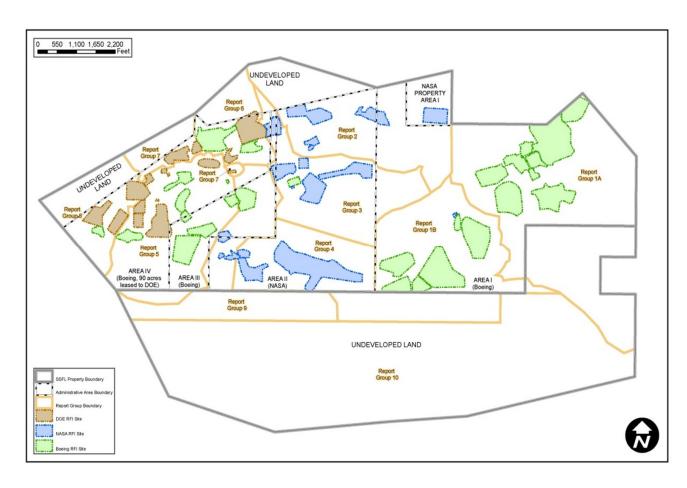


Distribution of Mapped Alluvium

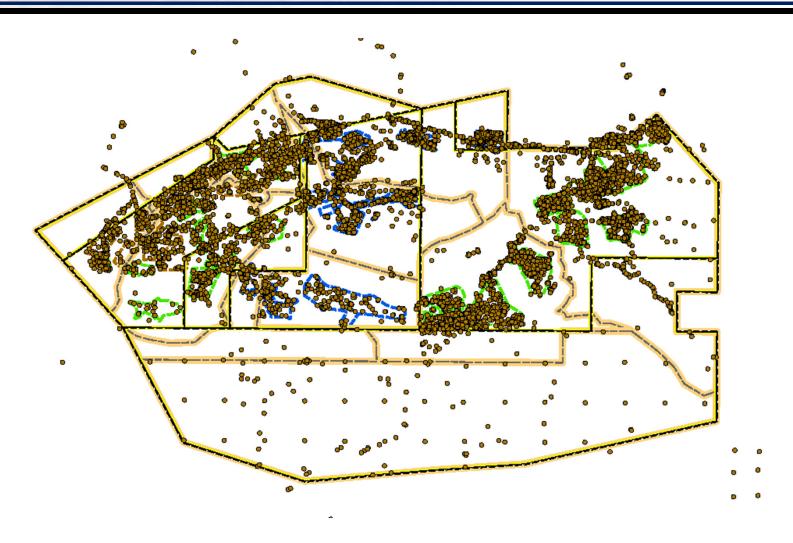


Surficial Media Investigation Groups and Sites

- Soil and groundwater RCRA cleanups
- 135 Source areas under investigation
- 11 investigation reports under agency review
- 13 Interim Measure clean ups completed
- > 70,000 cubic yards of soil remediated
- > 20,000 soil samples taken

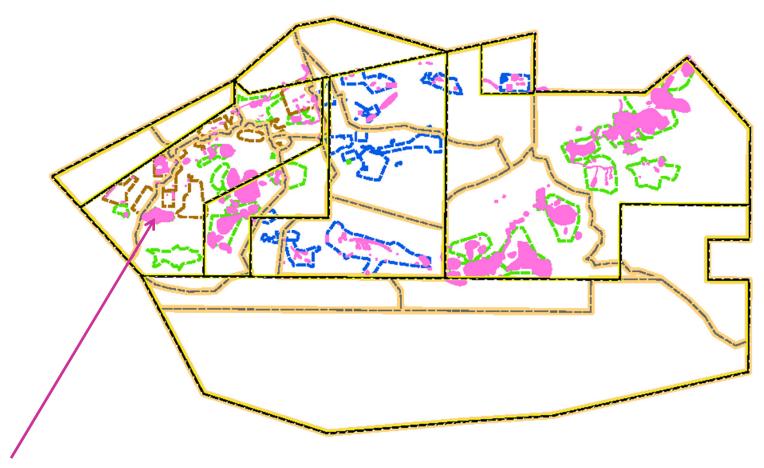


Surficial Media Sampling Locations



> 20,000 locations sampled

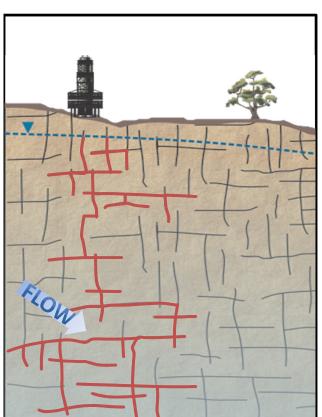
Surficial Media Contaminated Areas



Areas recommended for corrective measures study based on suburban residential land use

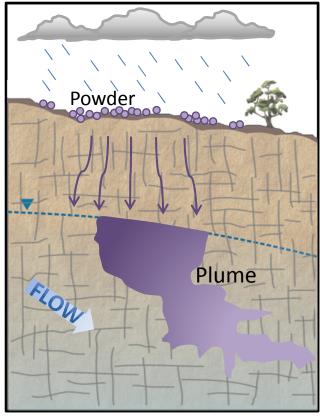
How Did Contaminants Get Into SSFL Groundwater?

DNAPL Infiltration



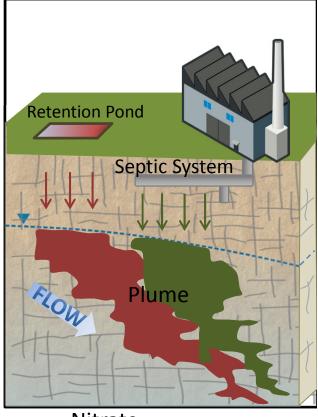
TrichloroethenePerchloroethene
Trichloroethane

Leaching of Solids



Perchlorate (ClO₄)
Metals

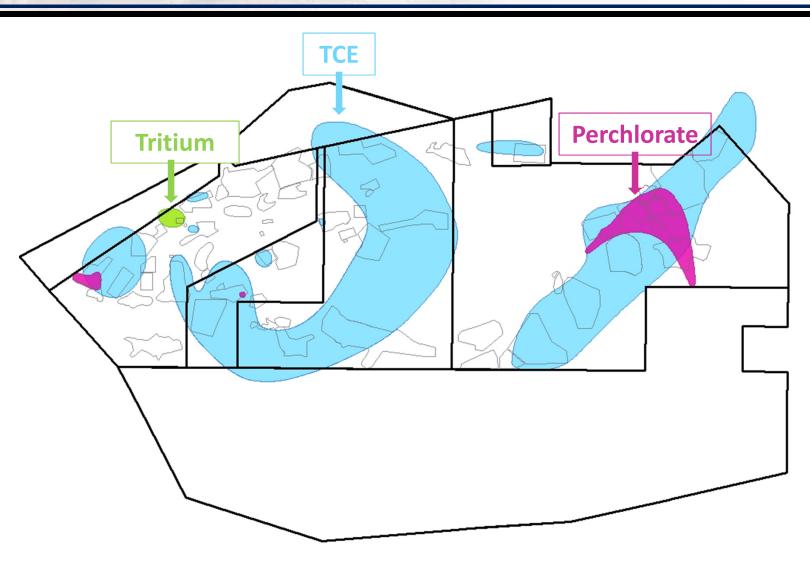
Water Infiltration



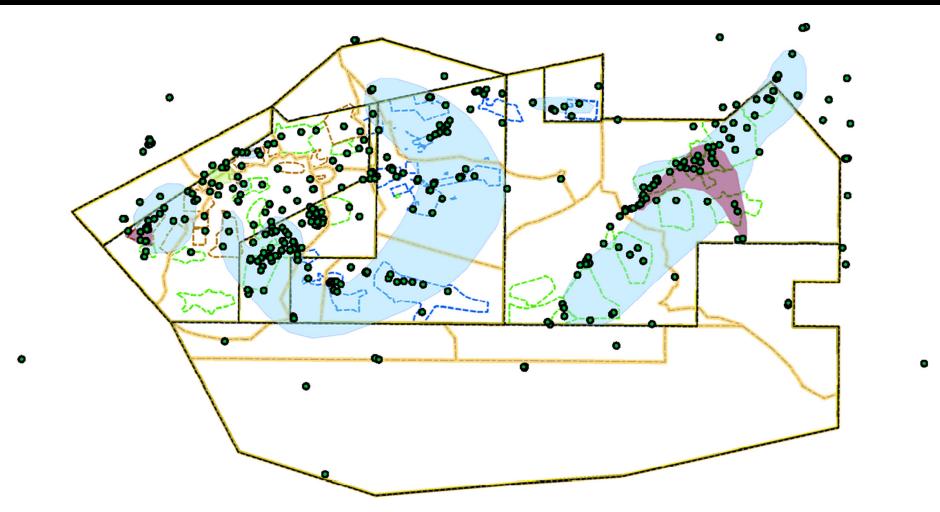
Nitrate Chloride **Tritium**

Dissolved Solvents

Extent of Key GroundwaterContaminants



Groundwater Monitoring Network



428 wells used to define extent of groundwater contamination

Processes Influencing Transport and Fate

How Contaminants Move - Transport Processes

- Advection (Flow)
 - Groundwater
 - DNAPL
- Molecular Diffusion

How Contaminants Change - Reaction Processes

- Sorption
 - Adsorption
 - Absorption
- Chemical Reactions
- Biological Reactions

Radioactive Decay



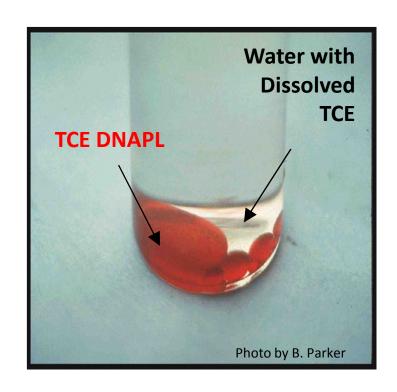
Terminology

DNAPL

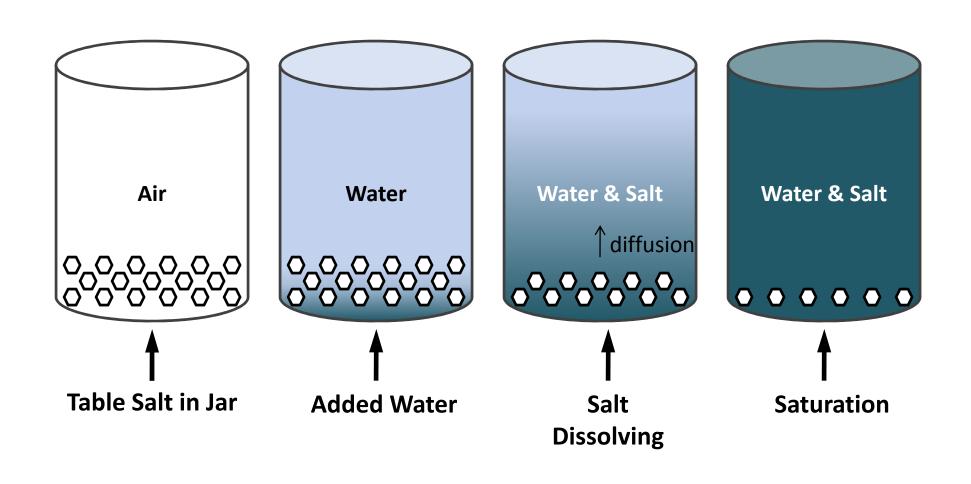
Dense Non - Aqueous Phase Liquid

DNAPL's = sinkers

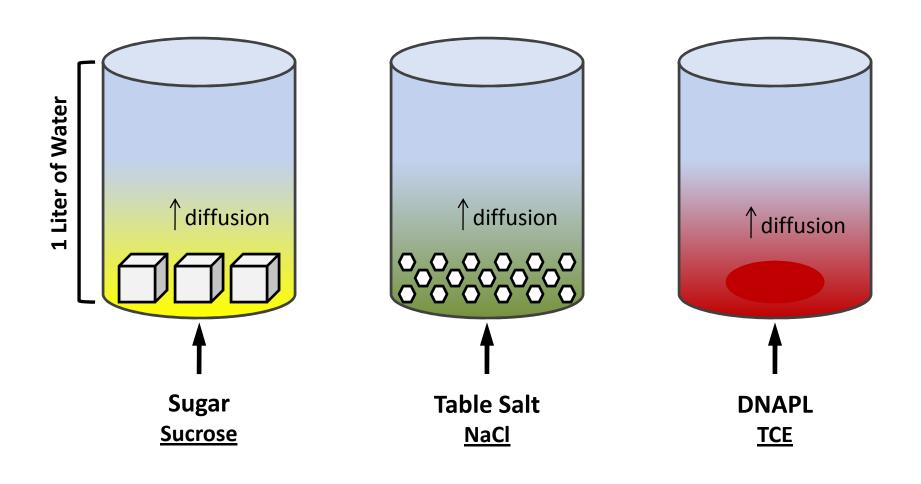
LNAPL's = floaters (petroleum products)



Dissolution to Saturation



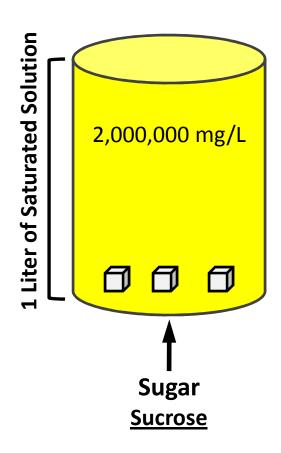
Dissolution and Diffusion

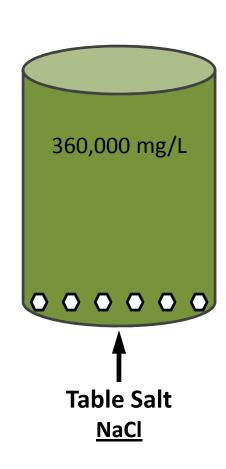


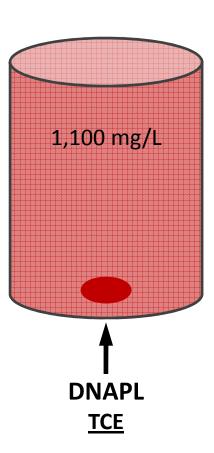


Solubility

Maximum Concentration Achieved





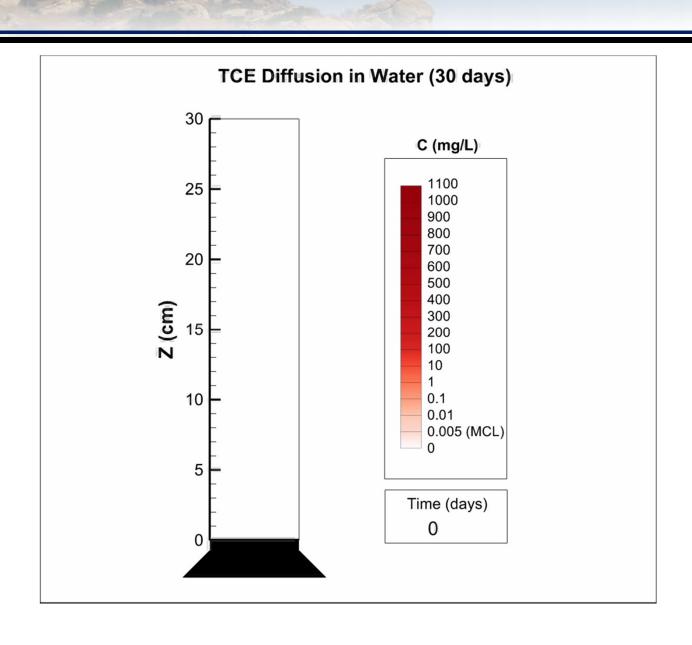




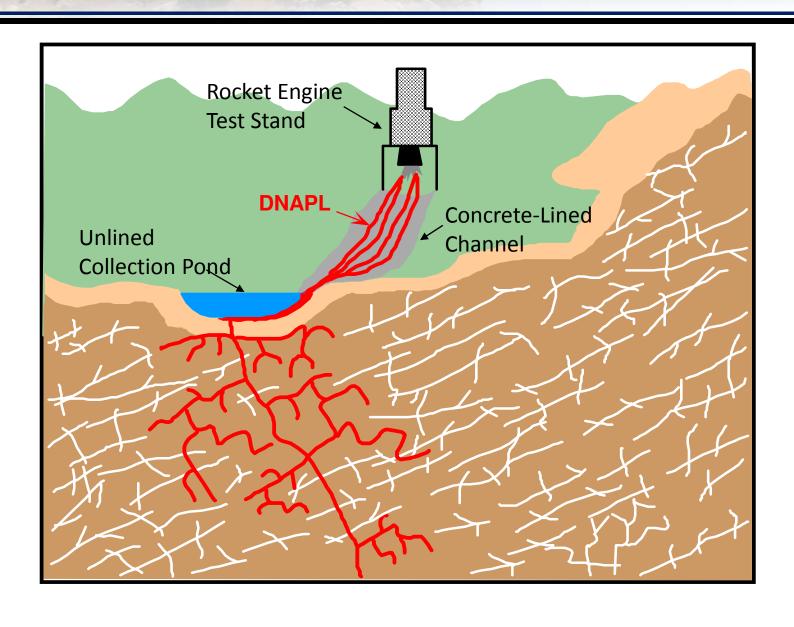
TCE will dissolve in water and can be measured over a large range of concentrations

Concentrations measured above the solubility limit (1,100 mg/L) indicate the presence of DNAPL

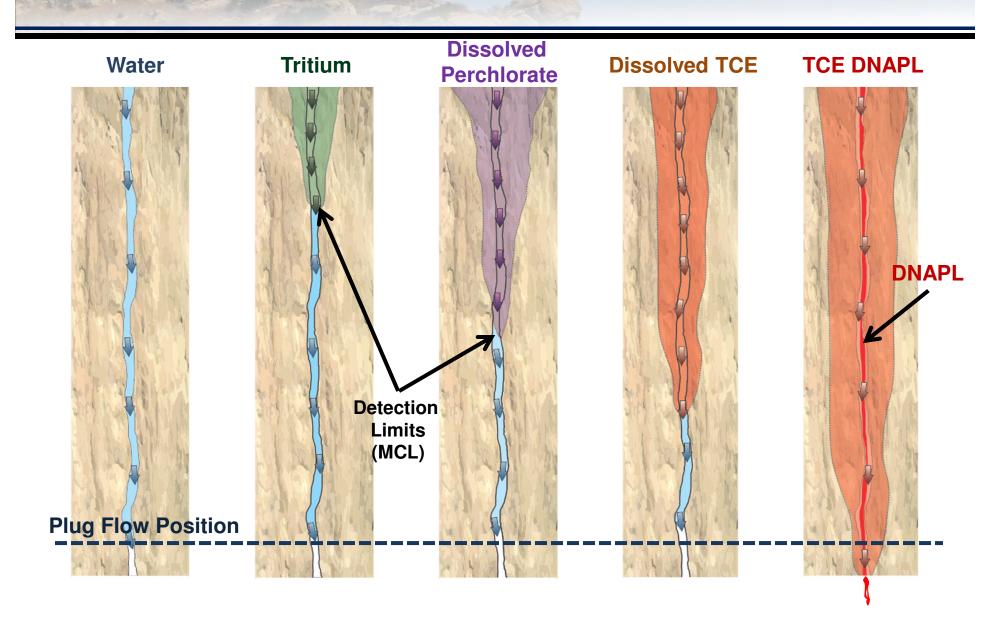
TCE Dissolution and Diffusion in Water



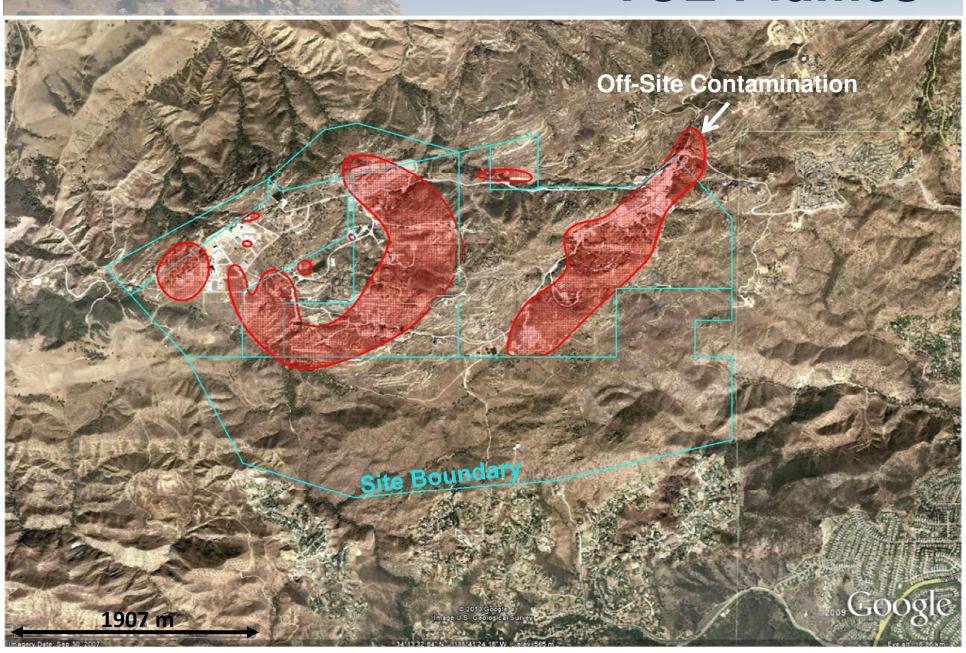
Rocket Test Stand



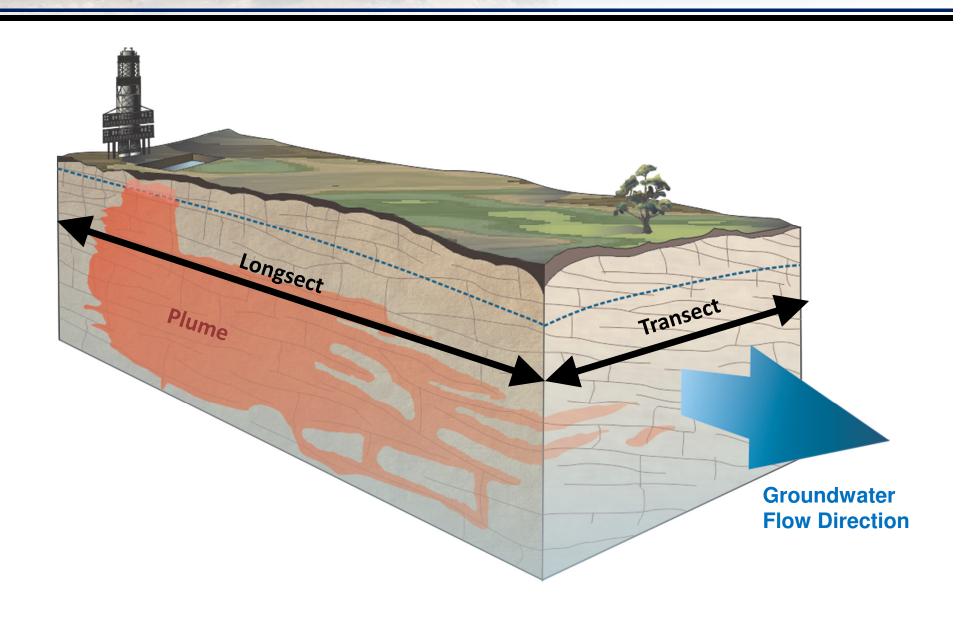
TCE is Most Mobile Contaminant Due to DNAPL



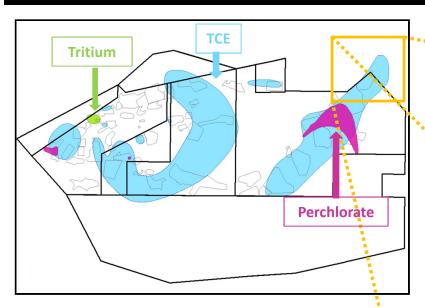
TCE Plumes

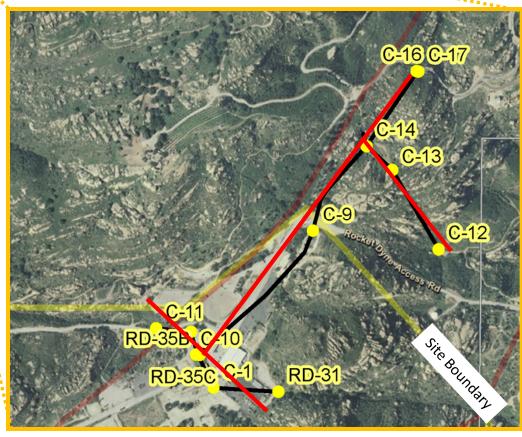


Schematic of TCE Plume at SSFL



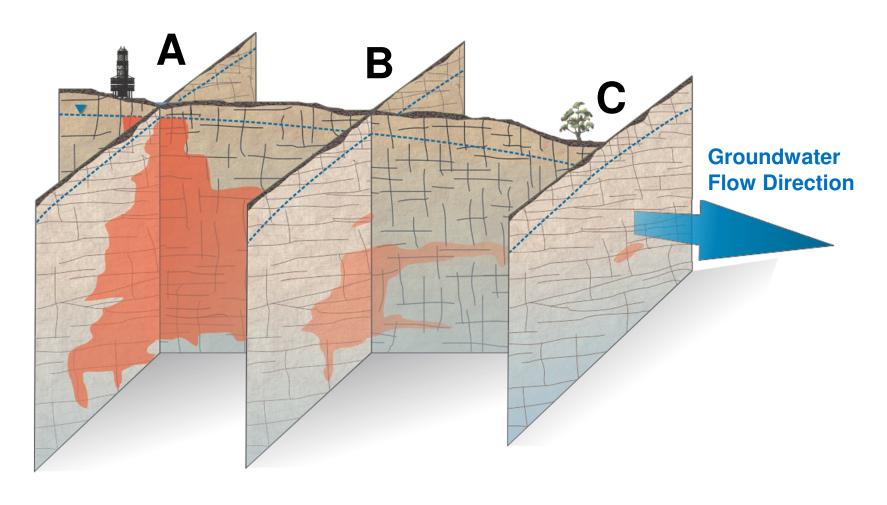
Focused Look at NE Plume



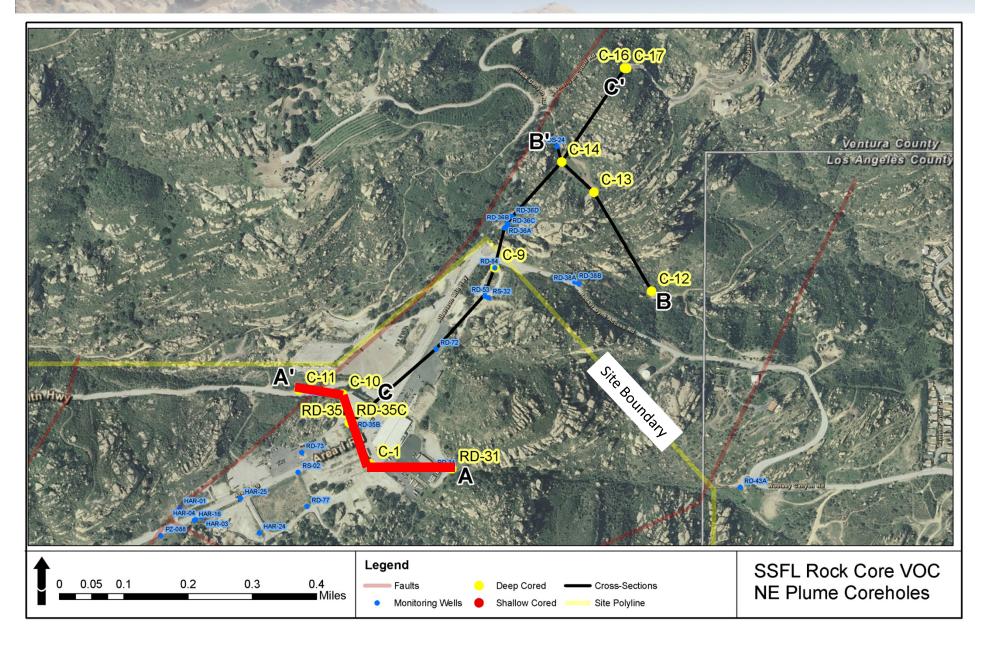




Transect is a vertical slice

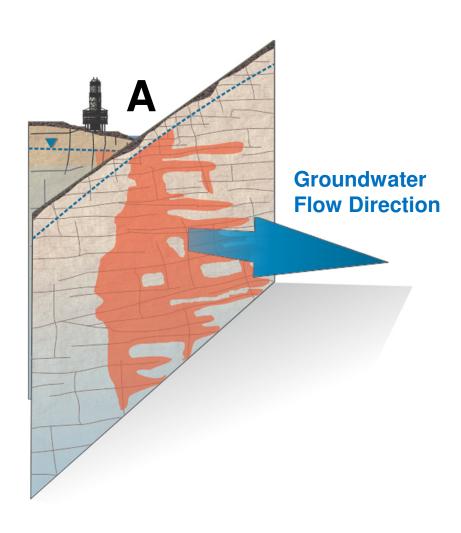


Source Zone Transect

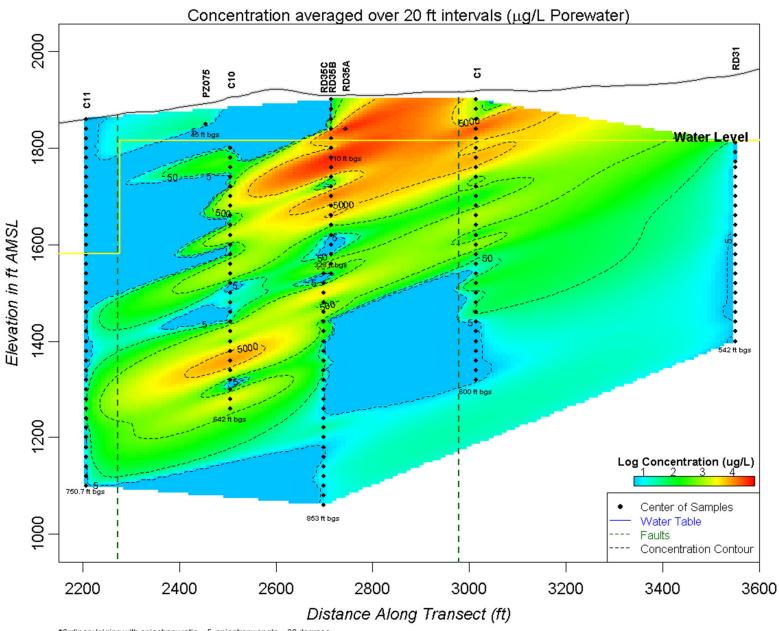




Source Zone Transect



Total Equivalent Porewater Concentration along Source Zone Transect



^{*}Ordinary kriging with anisotropy ratio = 5, anisotropy angle = 20 degrees

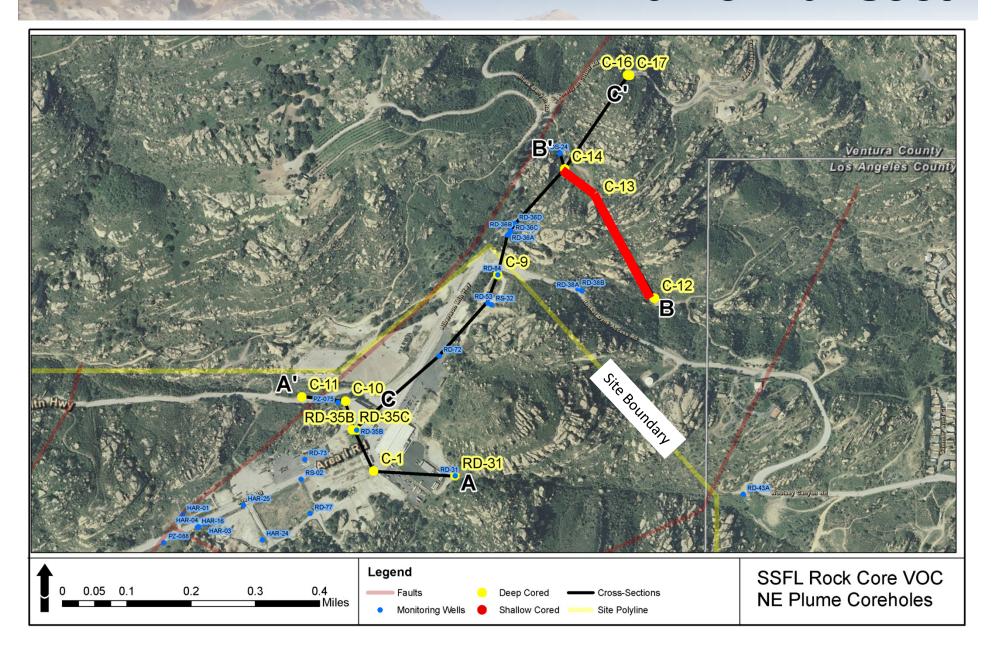


Most of the contaminant mass is in the upper 200 feet

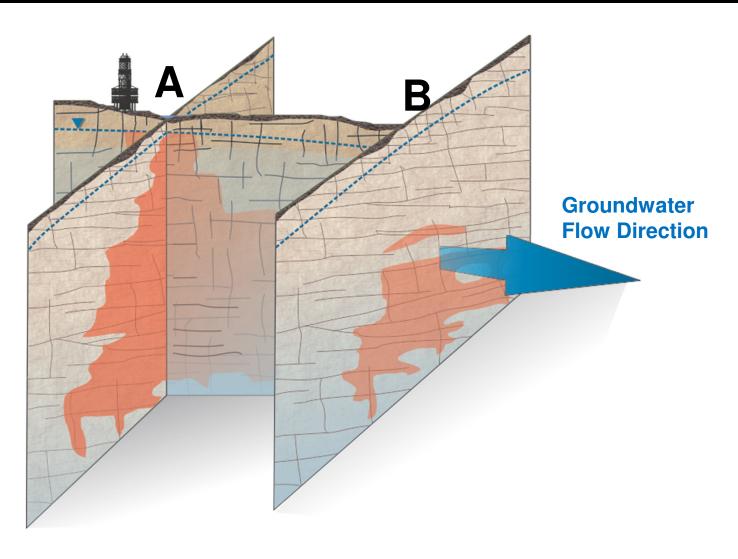
The width of the source zone is less than 1400 feet

Concentration distribution is influenced by geology

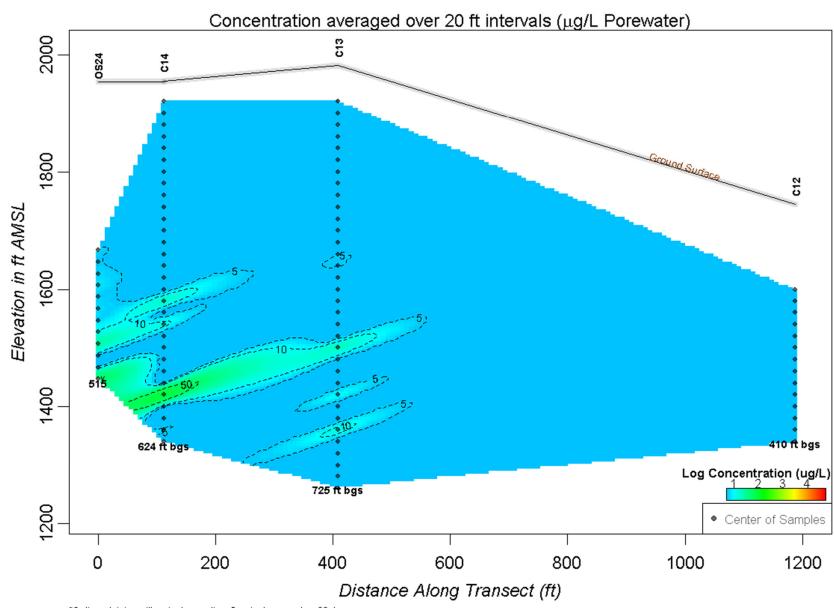
Plume Transect





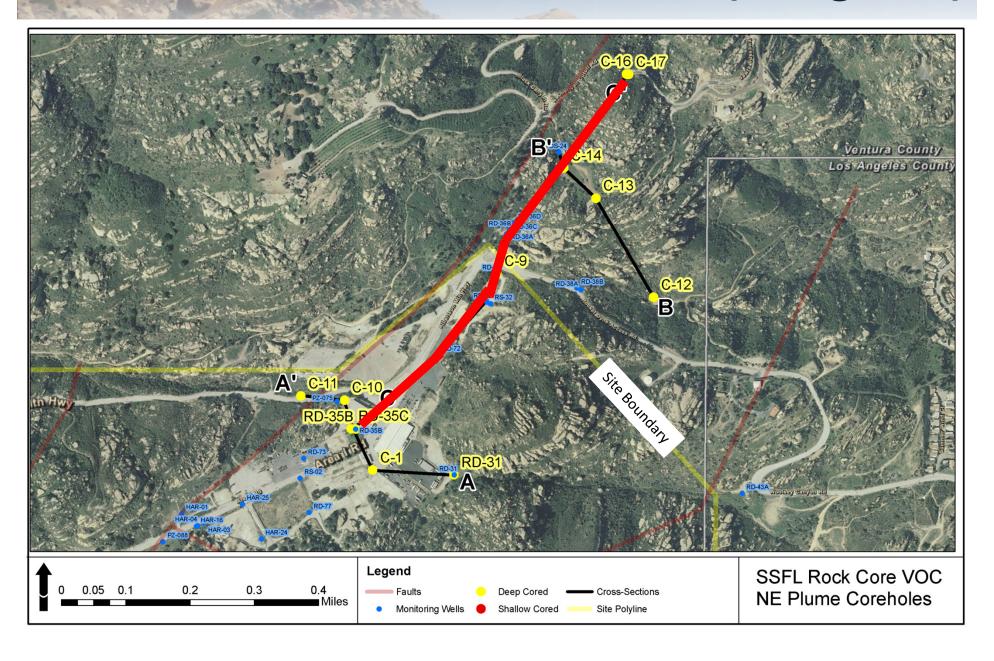


Total Equivalent Porewater Concentration along Plume Transect

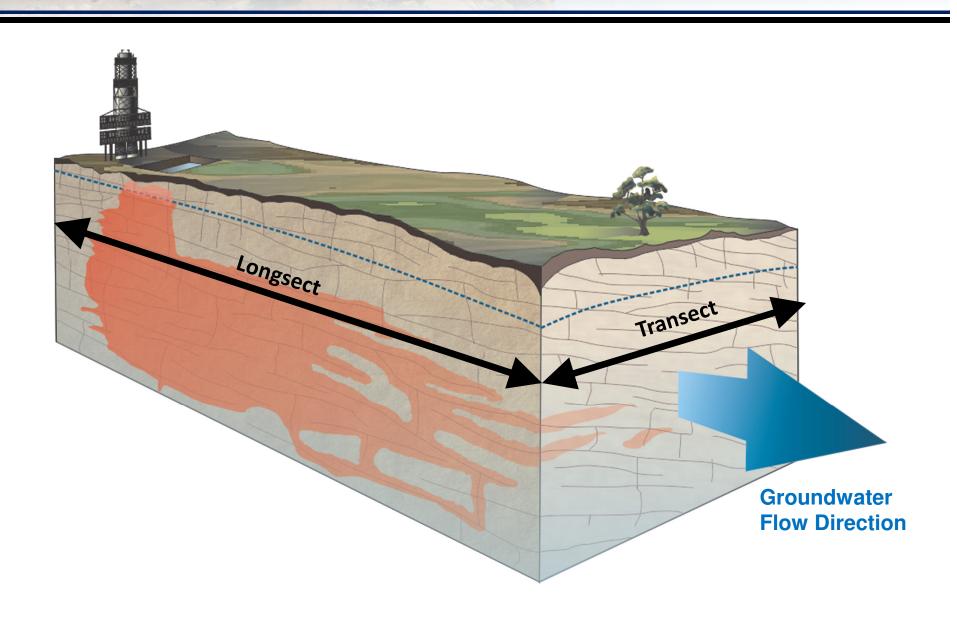


^{*}Ordinary kriging with anisotropy ratio = 5, anisotropy angle = 20 degrees

Plume Centerline (Longsect)



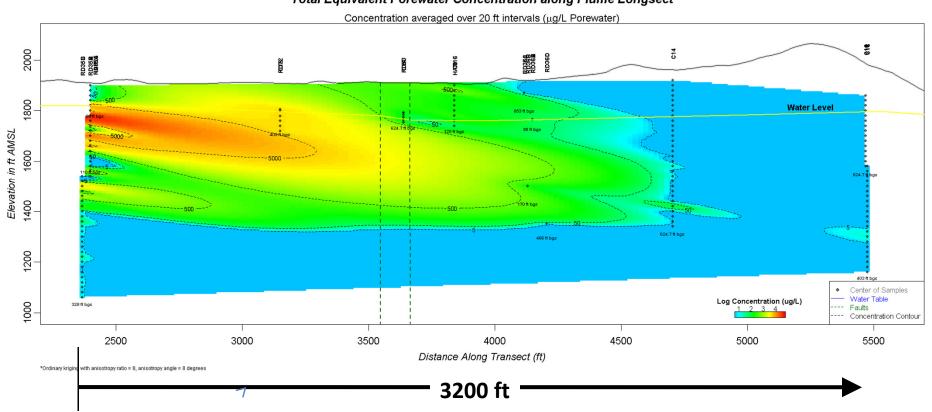
Schematic of TCE Plume at SSFL



TCE Migration Over 60 Years

Longsect

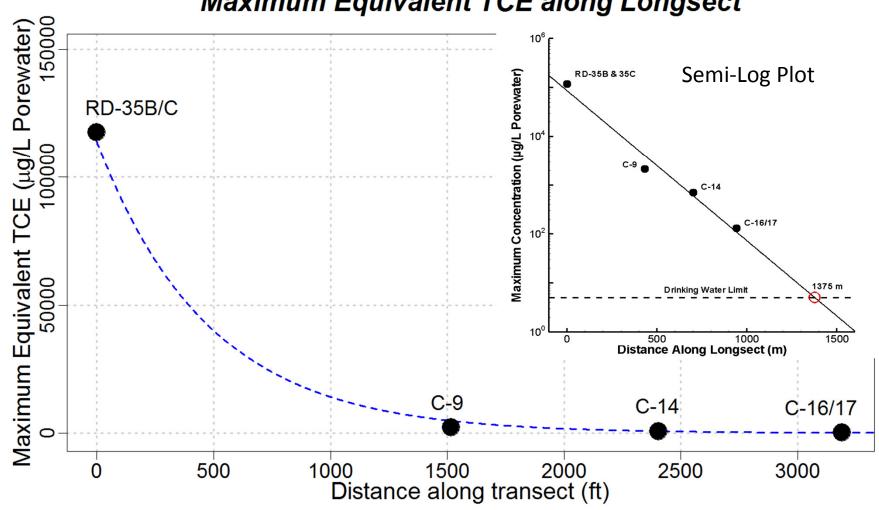
Total Equivalent Porewater Concentration along Plume Longsect



Groundwater Flow

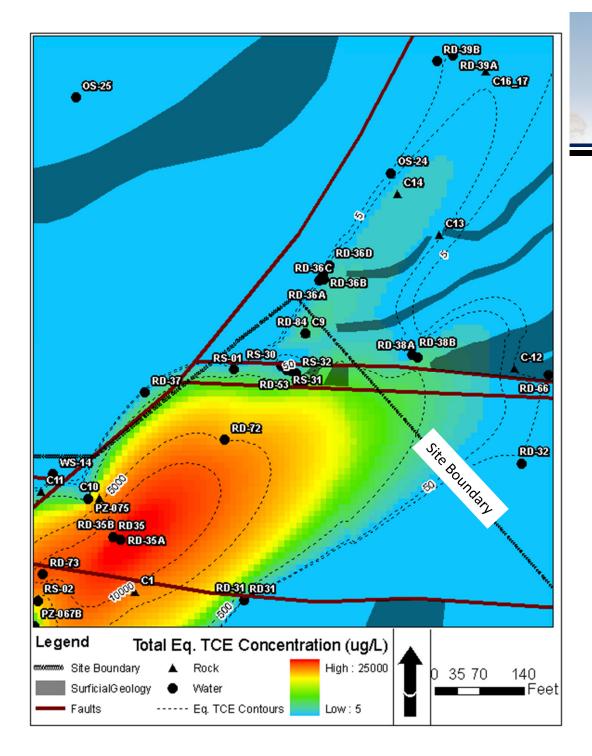
Concentrations Decline Rapidly with Distance from Source

Maximum Equivalent TCE along Longsect





Plume concentrations decline rapidly with distance in the direction of groundwater flow



Northeast Plume

Total Equivalent TCE (ug/L)

Rock Core and Groundwater Samples



Most of the contaminant mass is close to where it went into the ground.

Processes Influencing Transport and Fate

How Contaminants Move - Transport Processes

- Advection (Flow)
 - Groundwater
 - DNAPL
- Molecular Diffusion

How Contaminants Change - Reaction Processes

- Sorption
 - Adsorption
 - Absorption
- Chemical Reactions
- Biological Reactions

Radioactive Decay

DNAPL Dissolution in Sandstone

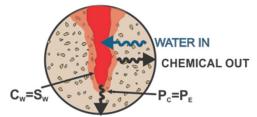
Organic Liqu

Introduction

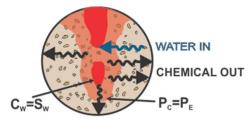
Much of
Europe has
clay or fract
siltstone, s
these geol
Flow, mu
blocks s
ectivitie
numer
Subst
organ
diffi

EARLY TIME

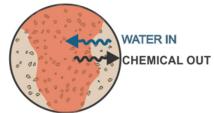
a) EARLY TIME: INTERCONNECTED DNAPL



b) INTERMEDIATE TIME: DISCONNECTED BLOBS



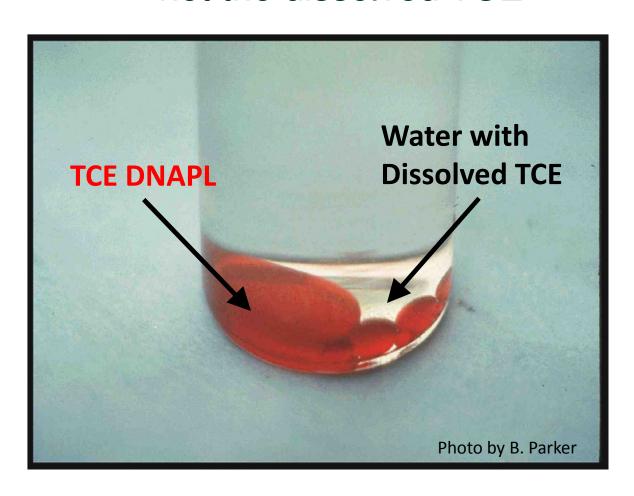
c) LATER TIME: DISSOLVED-PHASE ONLY

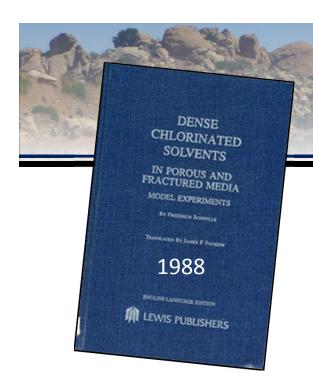


Parker et al., 1994

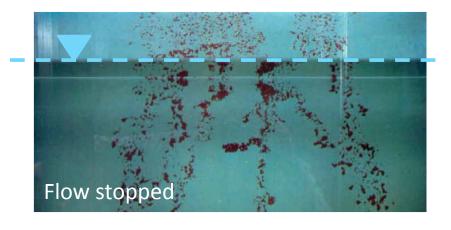
Dense Non Aqueous Phase Liquid

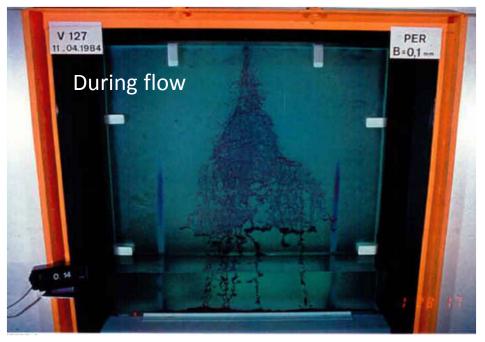
DNAPL Refers only to the immiscible liquid, not the dissolved TCE





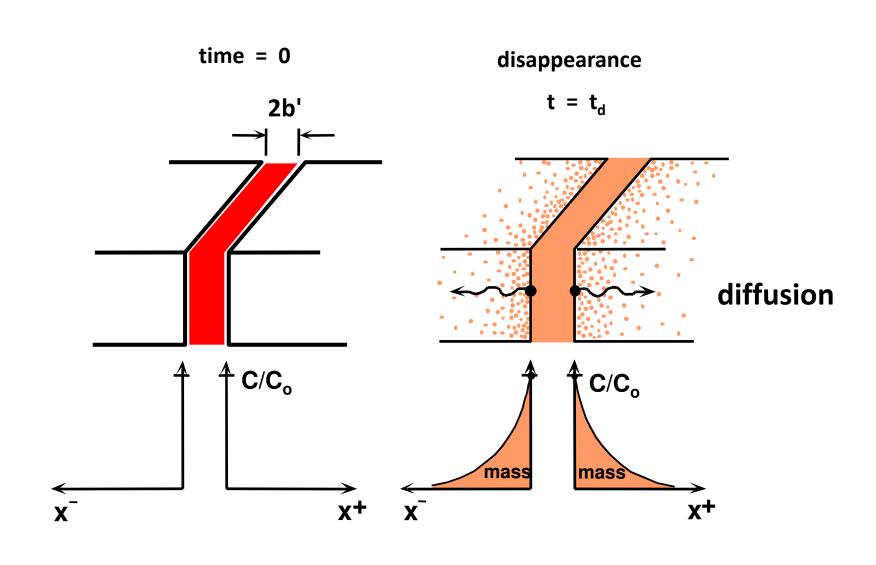
DNAPL Flow Experiment



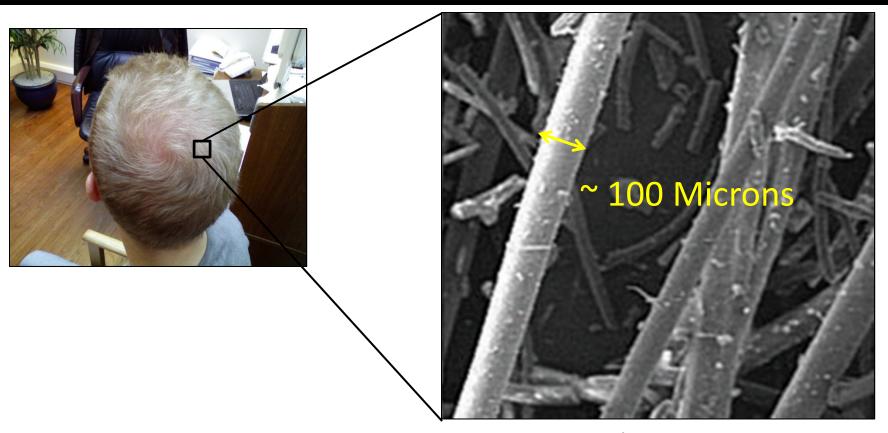


PCE **DNAPL** residual between rough-walled glass plates
100 micron fracture

DNAPL Dissolution and Diffusion



Aperture Size Concepts



1 micron = 1/1000 millimeters

SSFL Measured Fracture Apertures: 70 to 100 microns typical

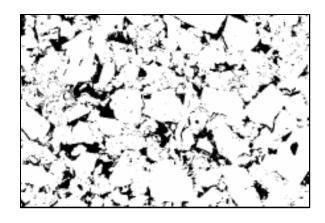


About 13 percent of the total rock volume is matrix void space.

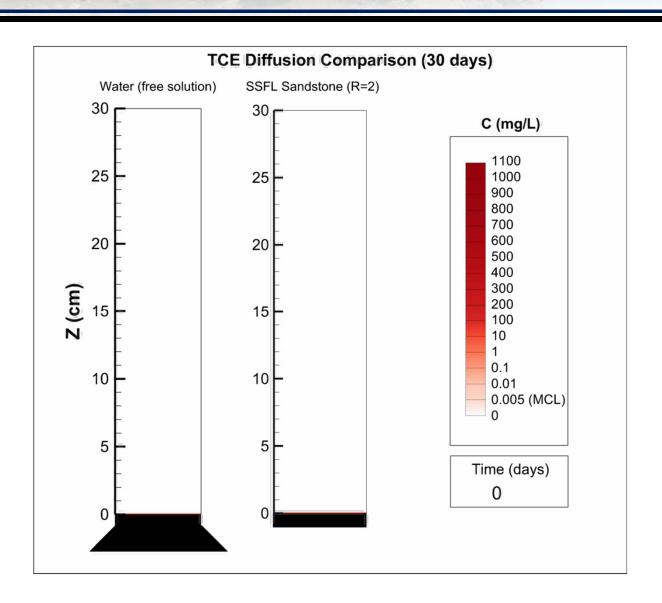
 $\Phi_{\rm m} = 0.13 (13\%)$







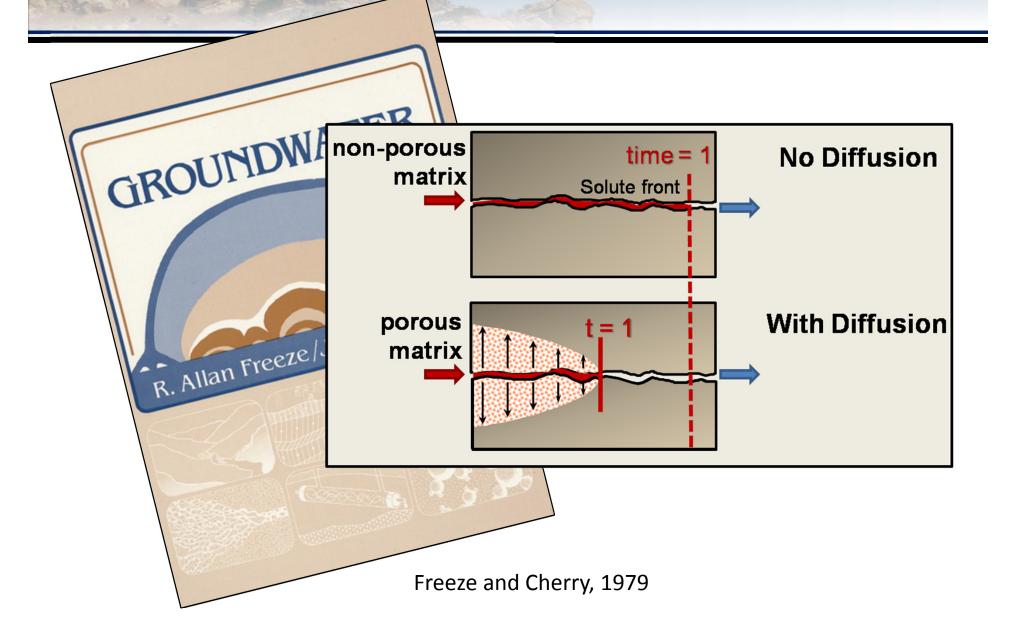
Diffusion in Water and SSFL Sandstone



SSFL Sandstone



Diffusion Slows Plume Fronts



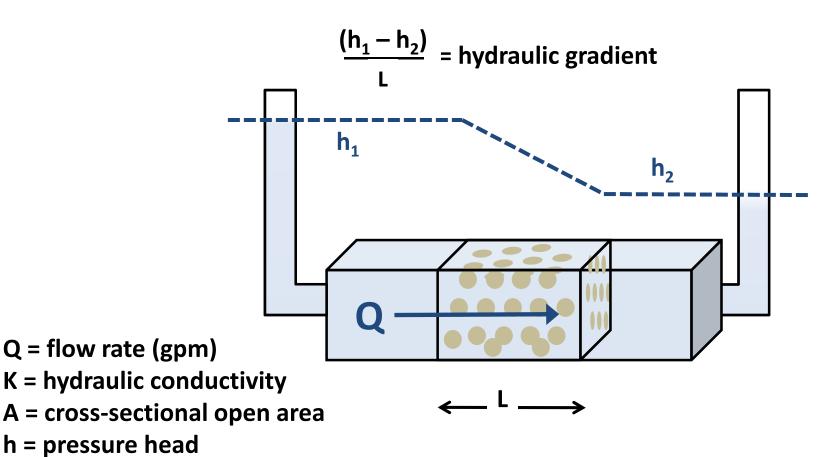


Diffusion of contaminants readily occurs in sandstone and shale.

Advection

Darcy's Law for Water Flow

$$Q = K \times A \times (h_1 - h_2)$$

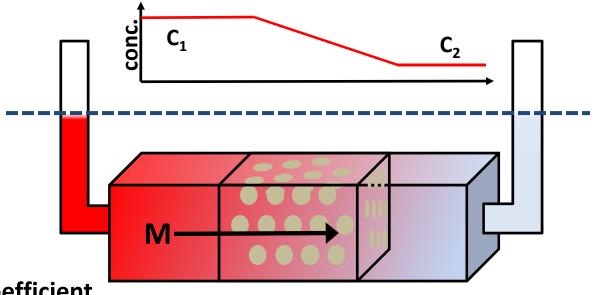


Molecular Diffusion

Fick's Law for Diffusion

$$M = D \times A \times (C_1 - C_2)$$

$$\frac{(C_1 - C_2)}{L} = concentration gradient$$



M = grams contaminant per day

D = effective diffusion coefficient

A = cross-sectional open area

C = chemical concentration

Processes Influencing Transport and Fate

How Contaminants Move - Transport Processes

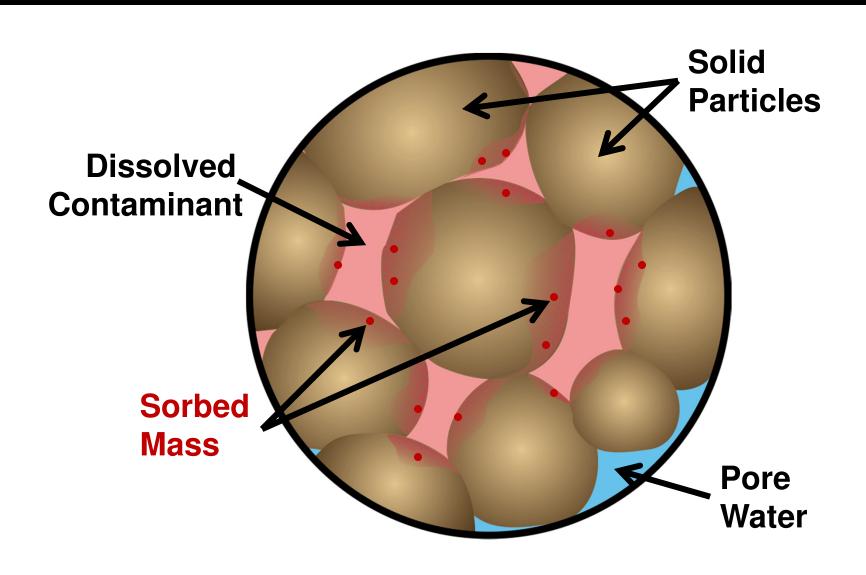
- Advection (Flow)
 - Groundwater
 - DNAPL
- Molecular Diffusion

How Contaminants Change - Reaction Processes

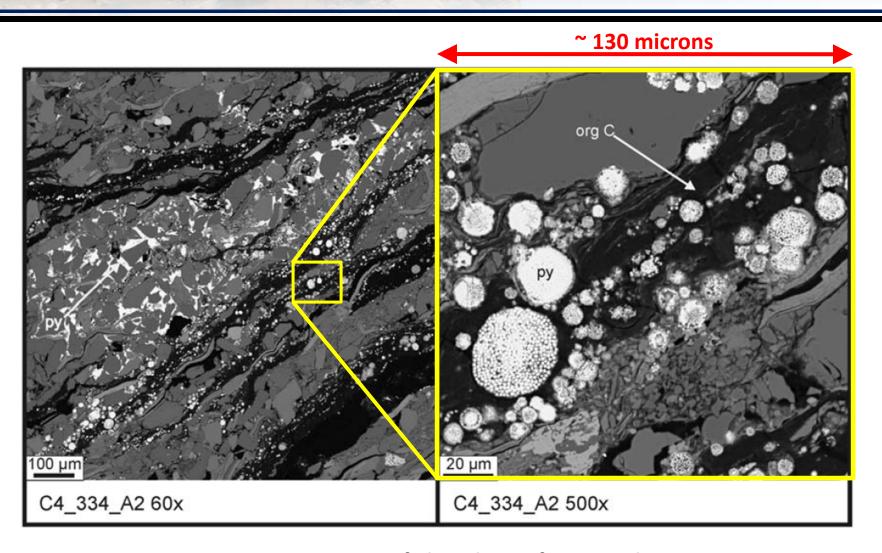
- Sorption
 - Adsorption
 - Absorption
- Chemical Reactions
- Biological Reactions

Radioactive Decay

Contaminant Sorption to Matrix Solids

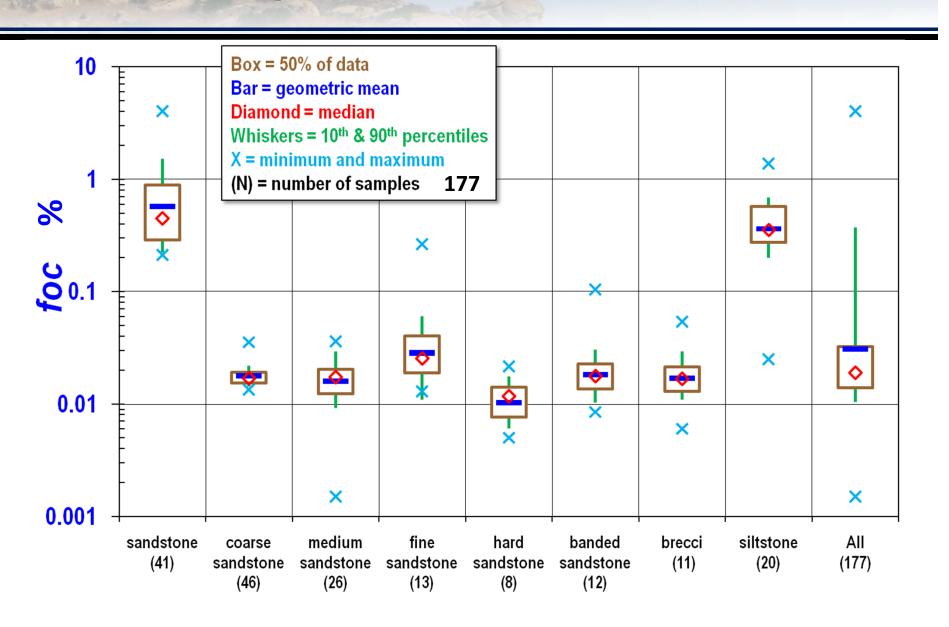


Solid Organic Carbon (foc) in Rock Matrix



SEM BSE Images of Thin Slices of SSFL Rock Core

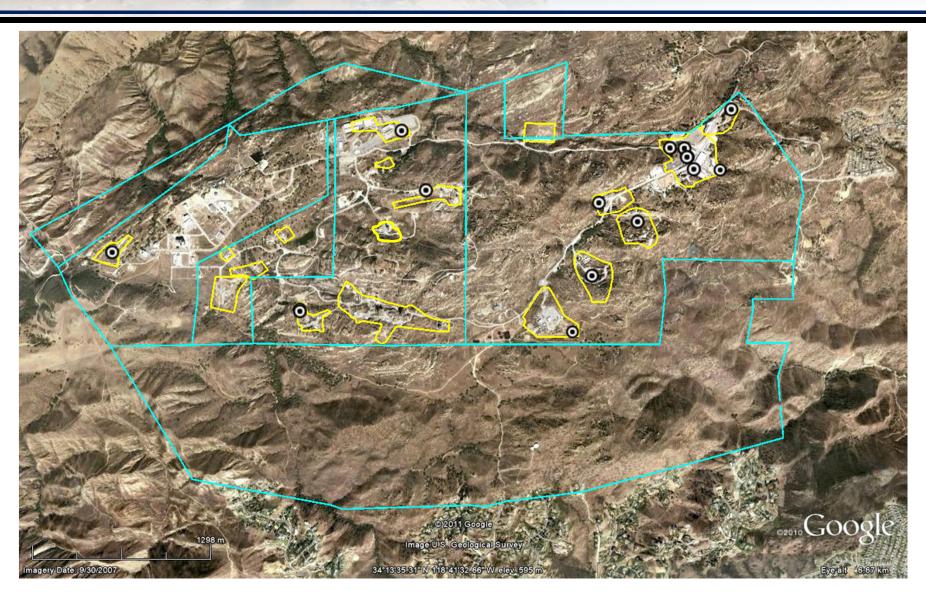
Solid Organic Carbon in Rock Matrix



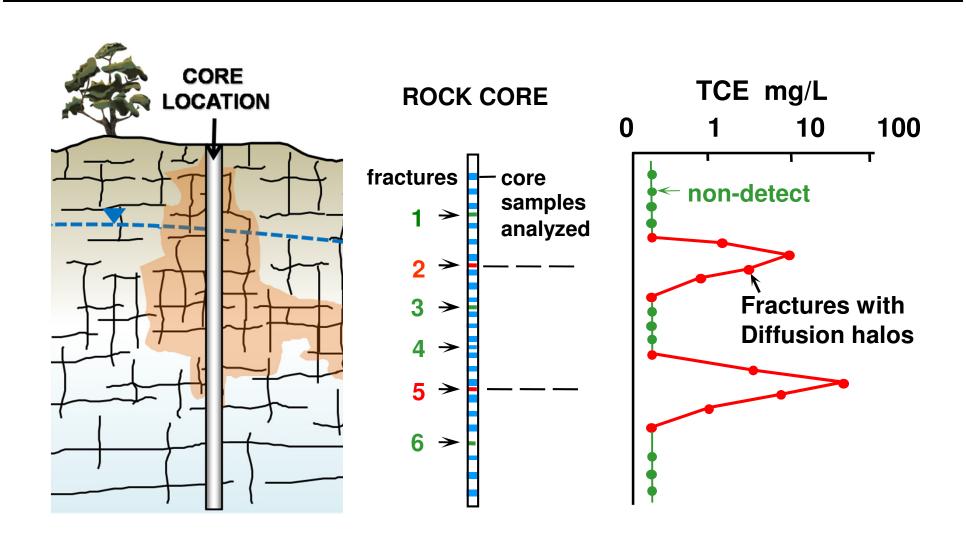


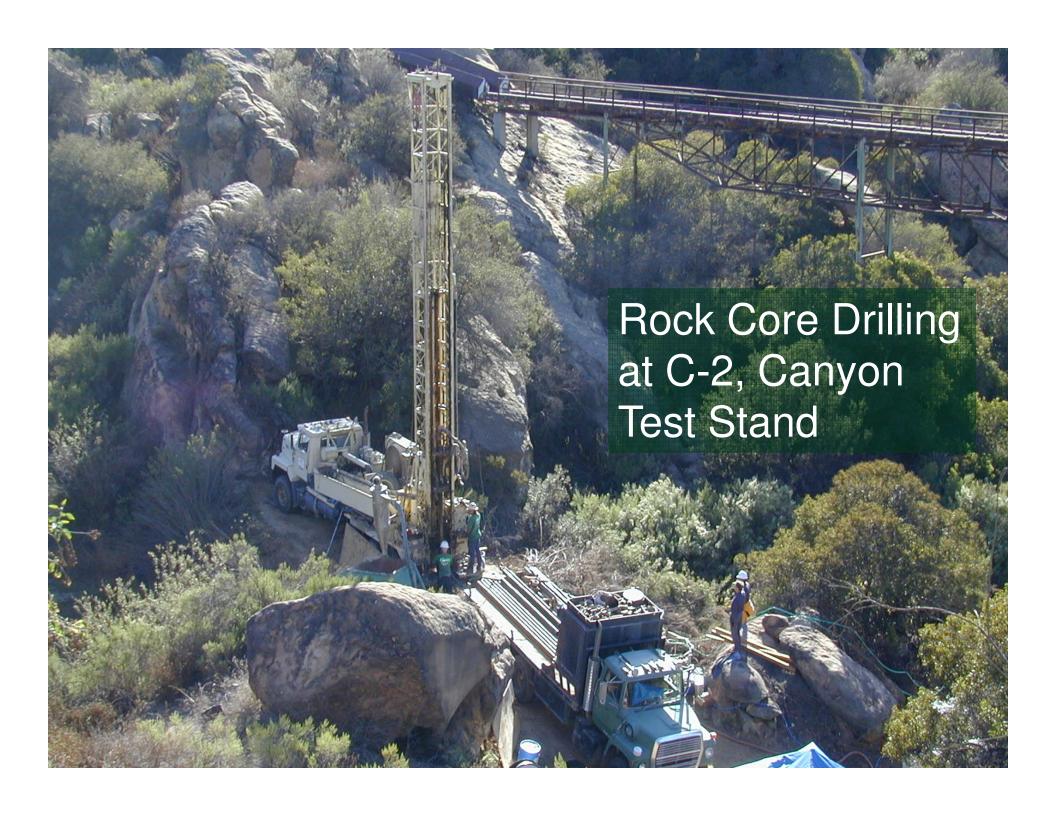
TCE and other organic contaminants readily sorb in Chatsworth Formation rock matrix

TCE Input Areas and Location of 15 Source Zone Core Holes



Rock Core Sampling to Find Contaminants





Core Collection and Inspection

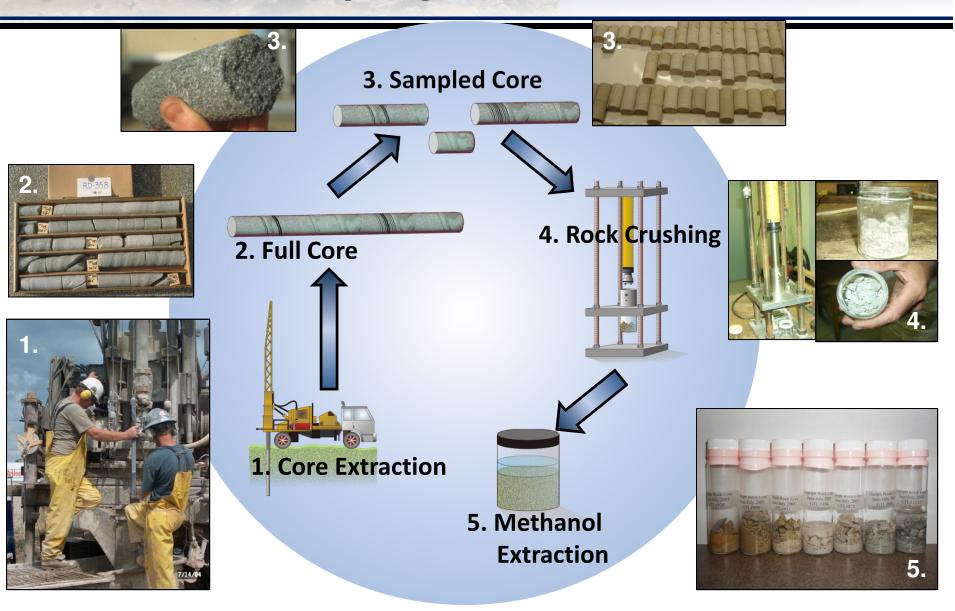


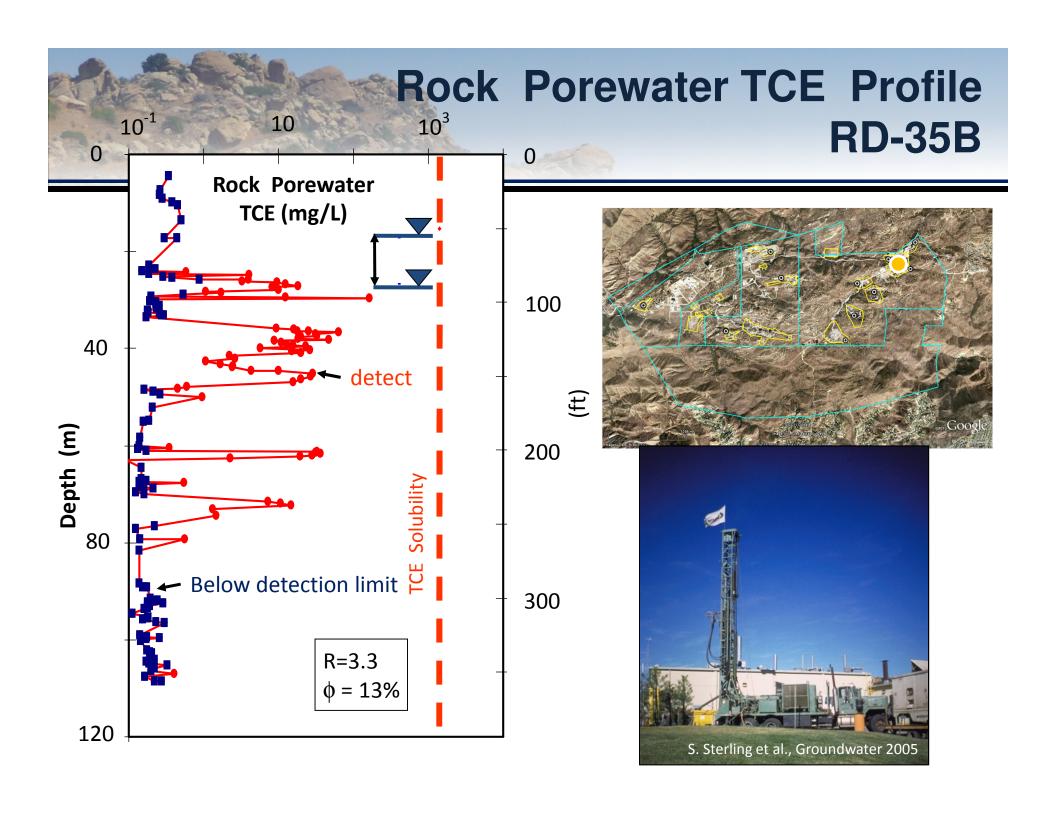
Core was collected in five foot lengths



Inspection of sandstone core

Rock Core Sampling and Preservation Method



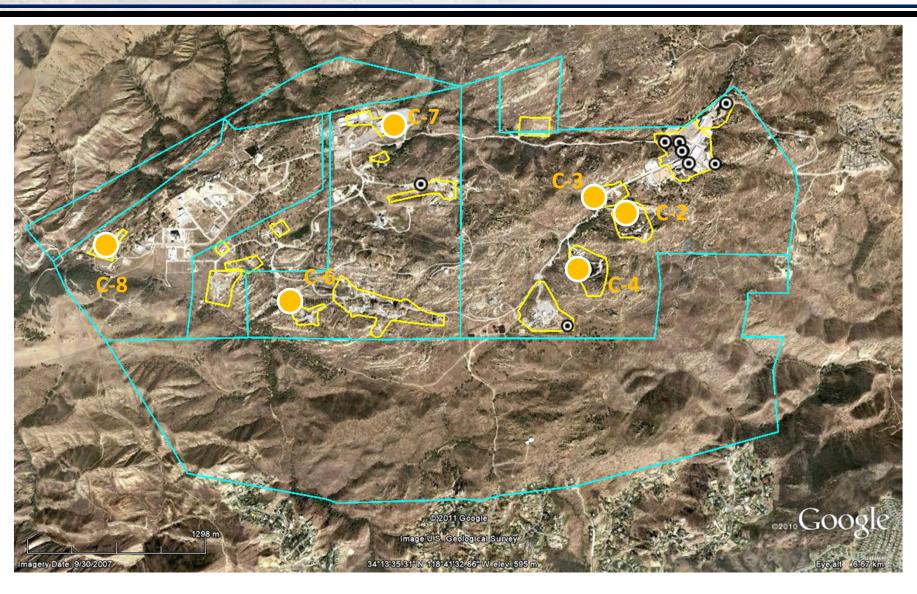


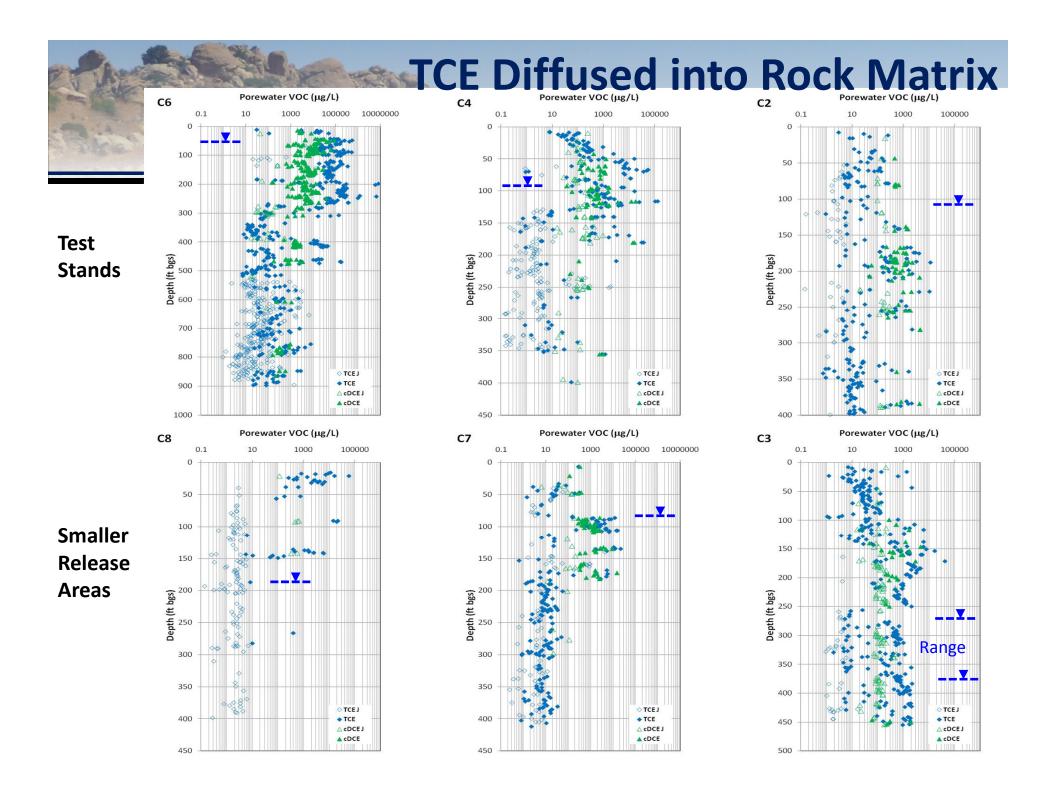


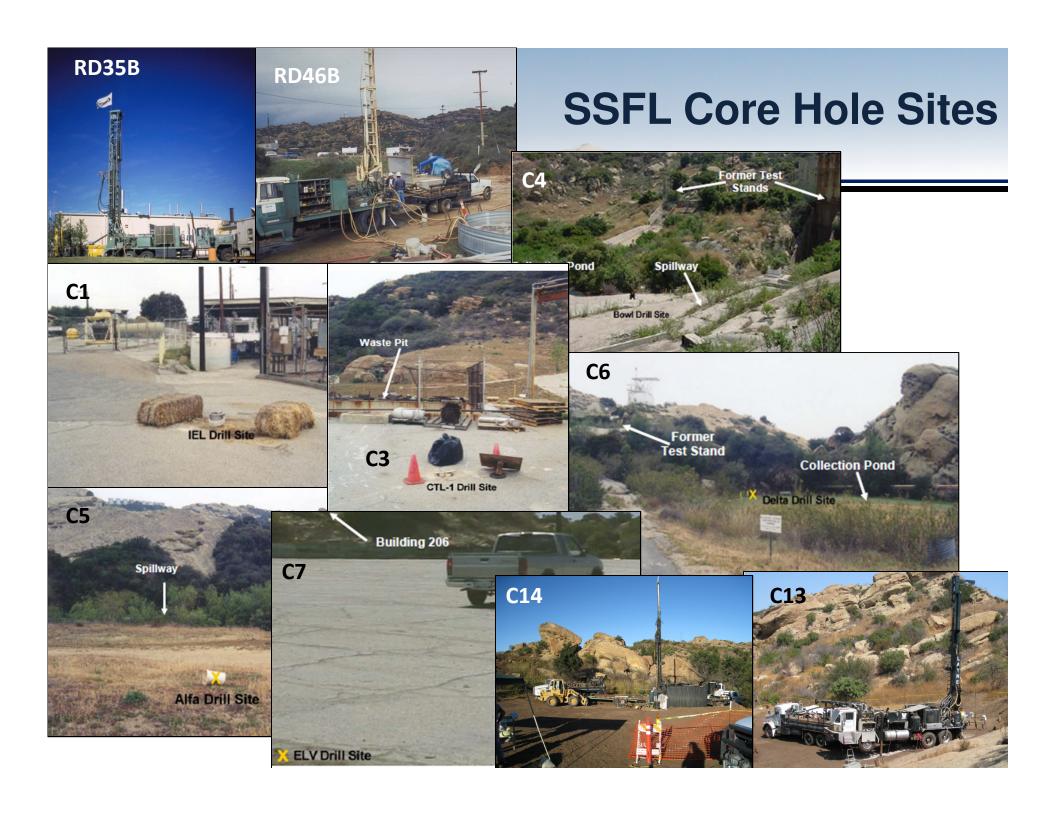
Rock core data show a lot of TCE mass in matrix

There is strong evidence that TCE as DNAPL has completely dissolved

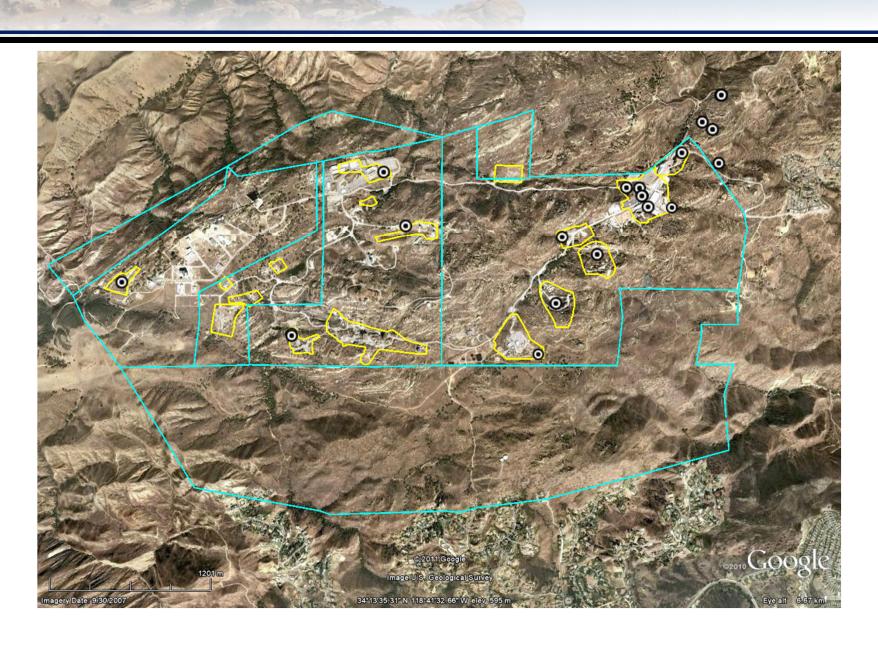
Rock Porewater TCE Profiles from 6 Source Zones





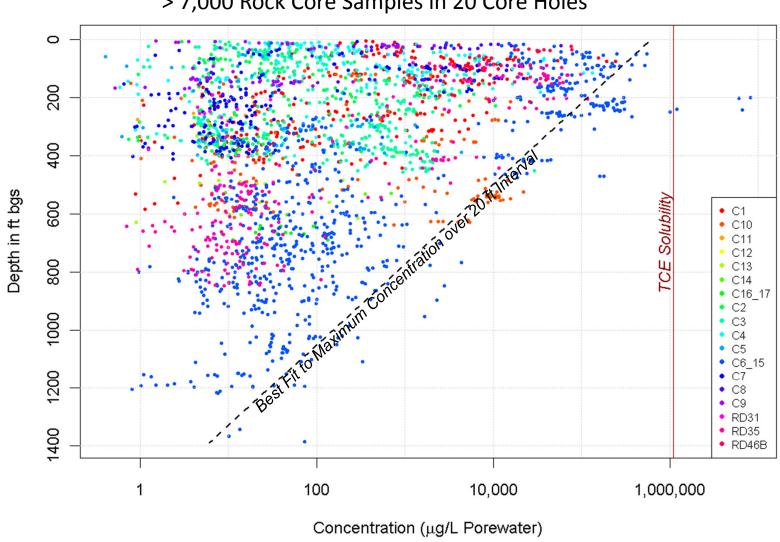


Total of 20 Coreholes at 18 Locations



TCE Concentrations Decline with Depth

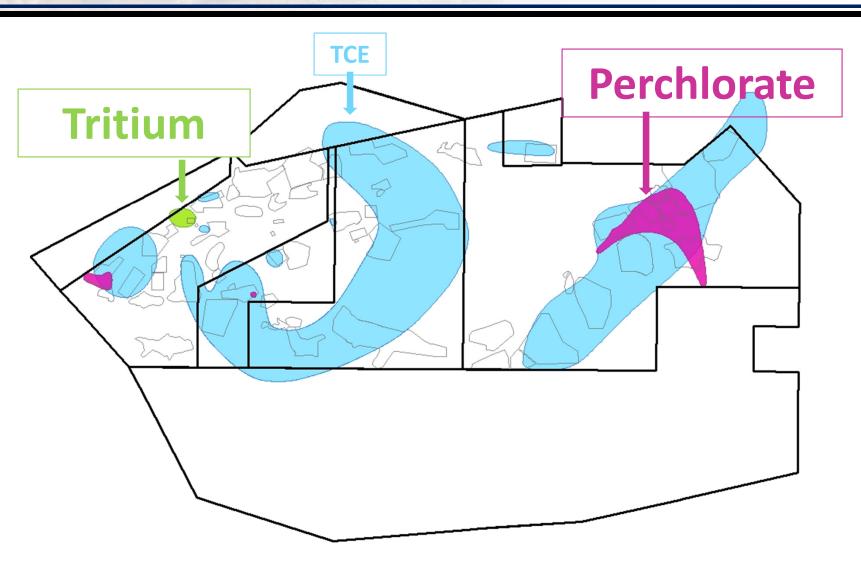


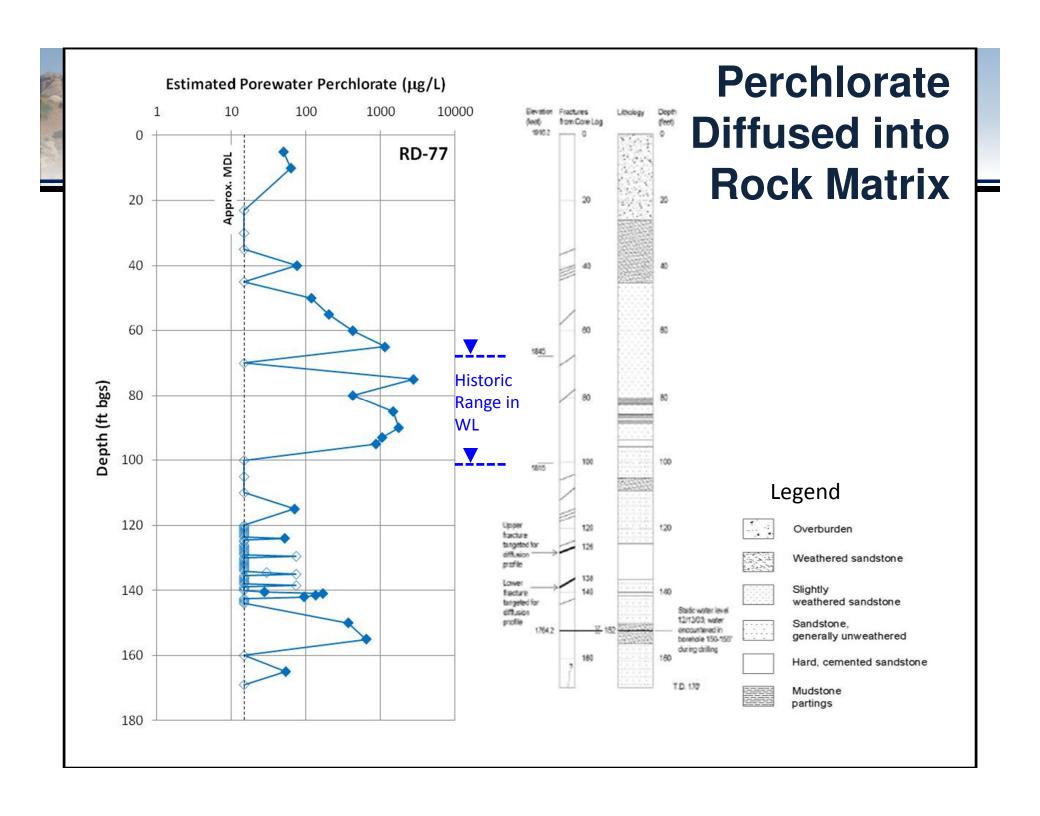


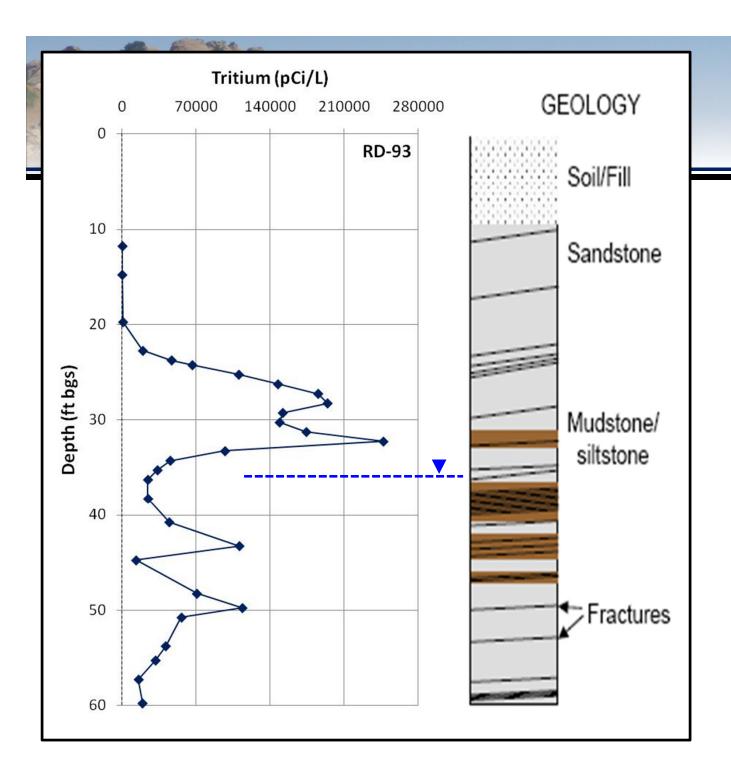


Over 7,000 rock core samples show highest concentrations are shallow and diminish strongly with depth

Other Key Groundwater Contaminants

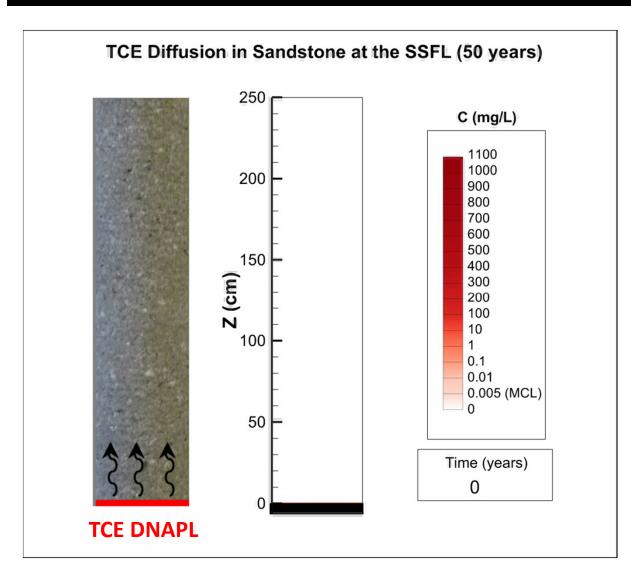






Tritium Diffused into Rock Matrix

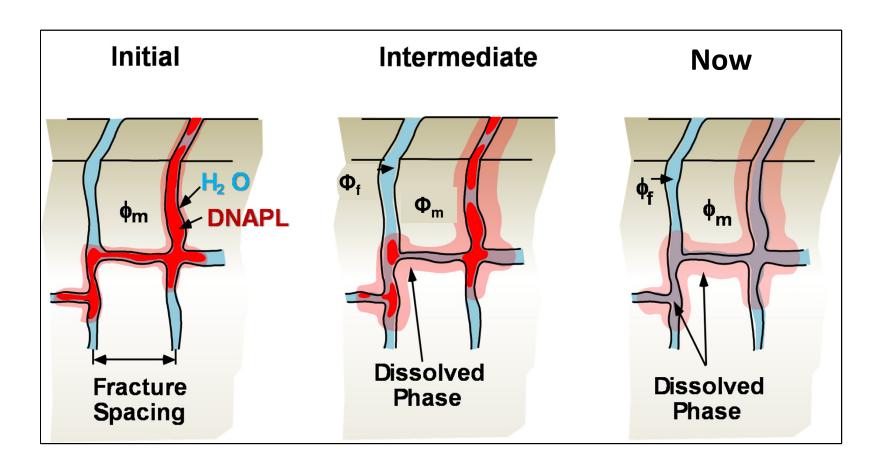
Key Finding



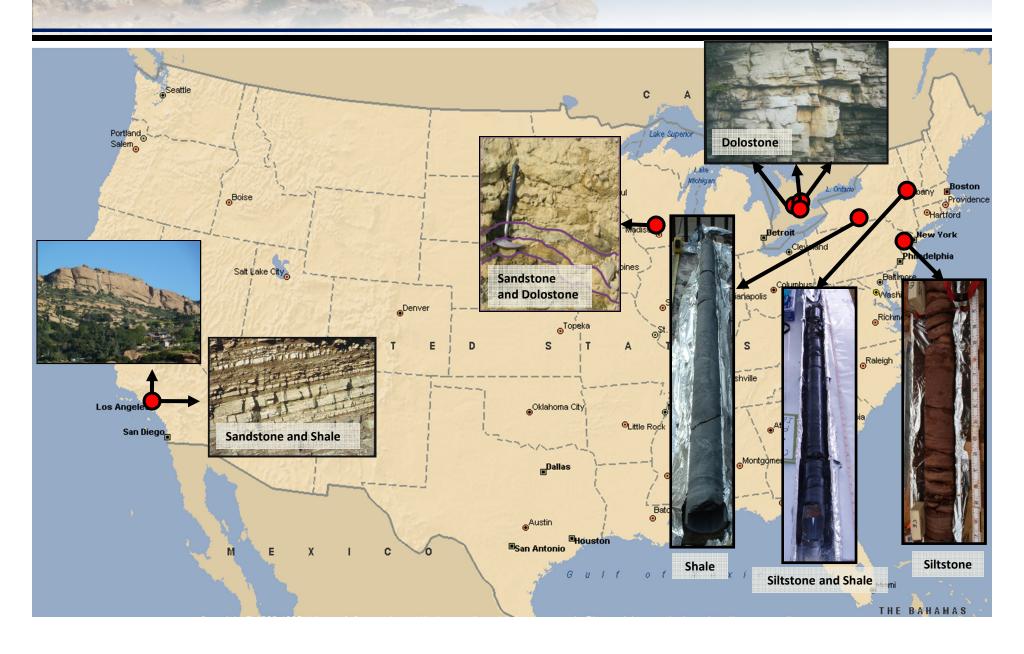
Diffusion of contaminants readily occurs in sandstone and shale and is a very important process at SSFL.

Key Finding

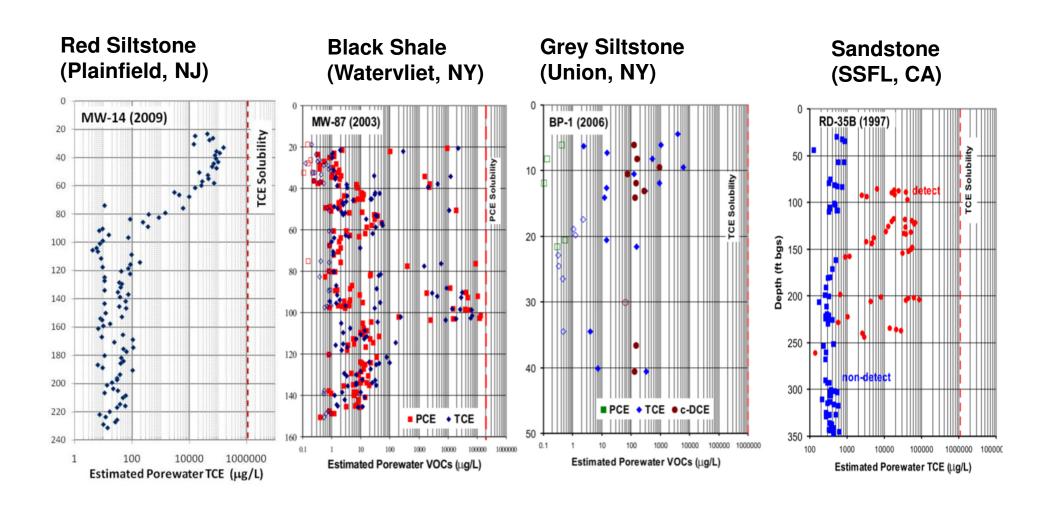
Nearly all the contaminant mass is in the rock matrix between the fractures.



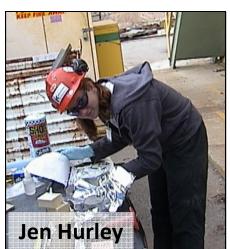
Similar Results From 7 Other Sites



Rock Core VOC Results at 4 of 8 Sites



Research Projects & Student Theses



Laura Zimmerman

Sean Sterling
Jen Hurley
Amanda Pierce
Laura Zimmerman
Pete Pehme
Jessica Meyer
Glaucia Lima
Pat Quinn

M.Sc. Thesis
M.Sc. Thesis
M.Sc. Thesis
M.Sc. Thesis
M.Sc. Thesis
PhD Student
PhD Student
Post Doc
Post Doc



1999

2003

2005

2010

Present

Present

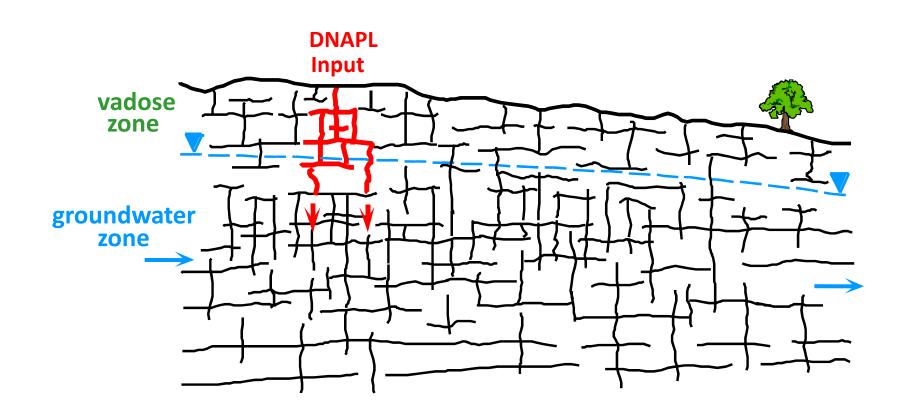
Present

Present

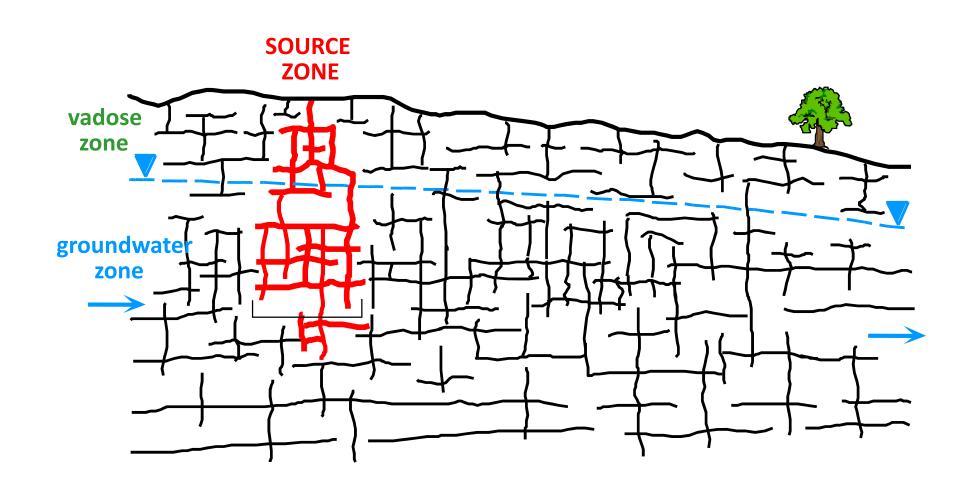




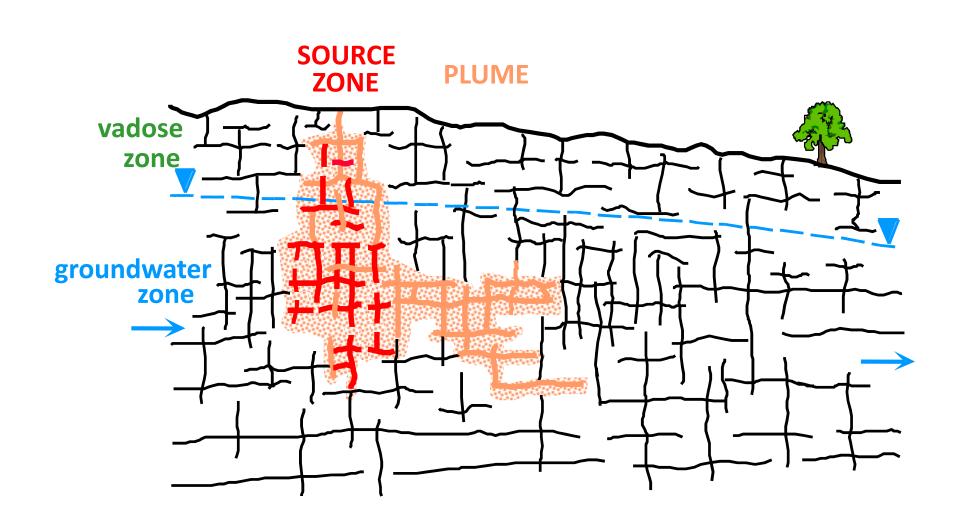
Stage 1: DNAPL Enters and Moves along Fractures



Stage 2: Immobilized DNAPL Dissolves

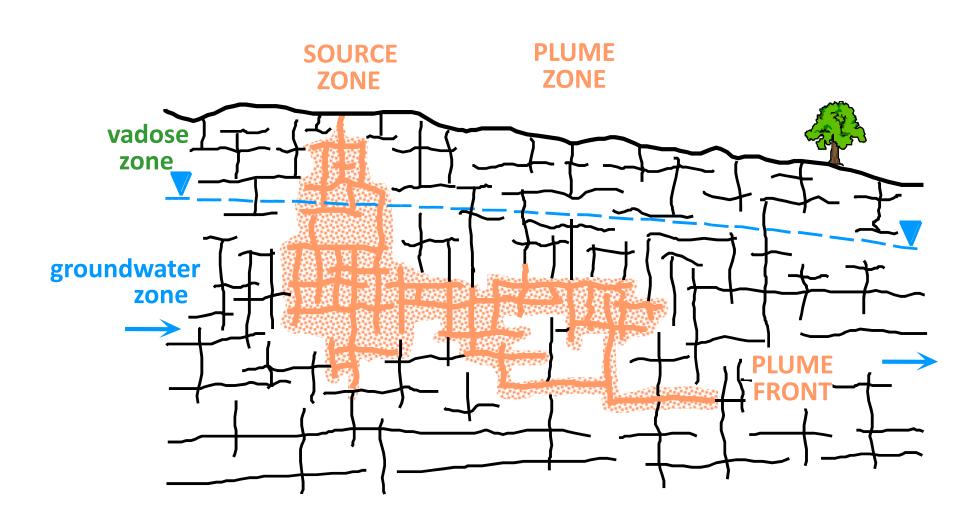


Stage 3: Dissolved TCE Moves along fractures and diffuses into matrix

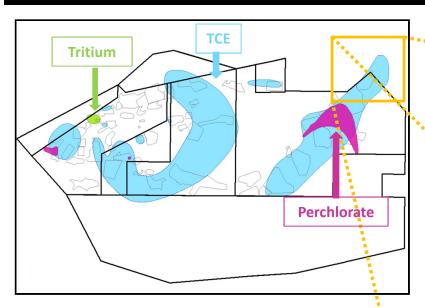


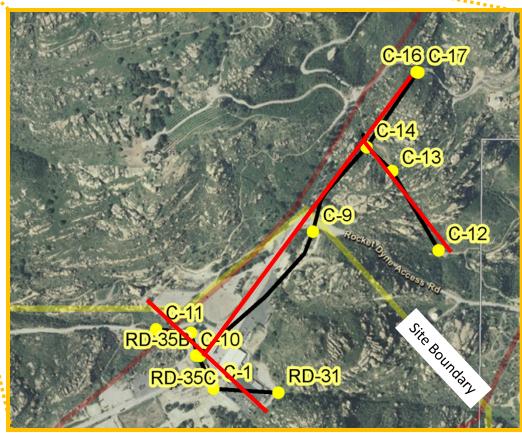
Stage 4: No DNAPL remains and plume front slows

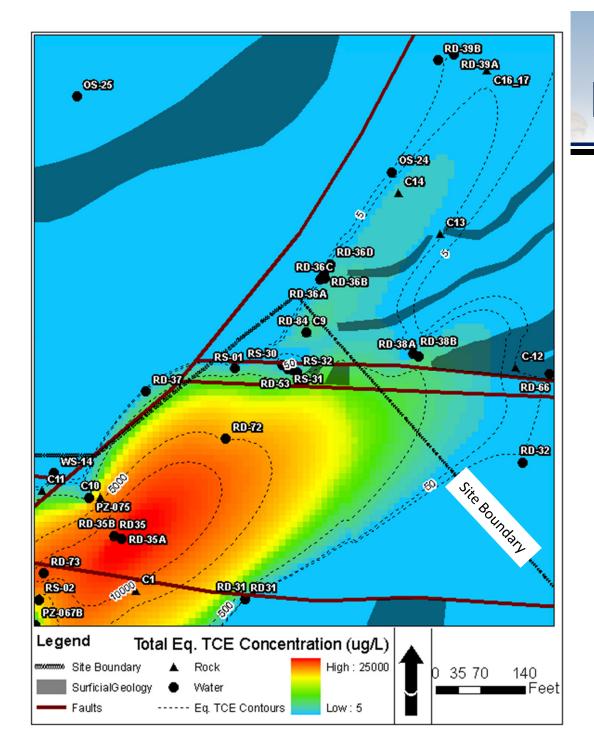
SSFL is in Stage 4



Focused Look at Northeast Plume





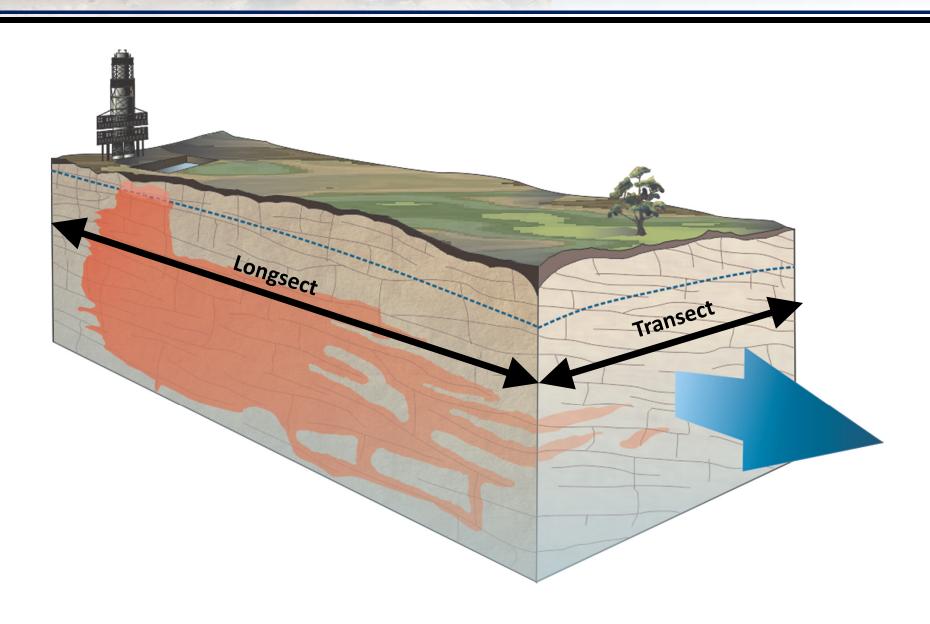


Northeast Plume

Total Equivalent TCE (ug/L)

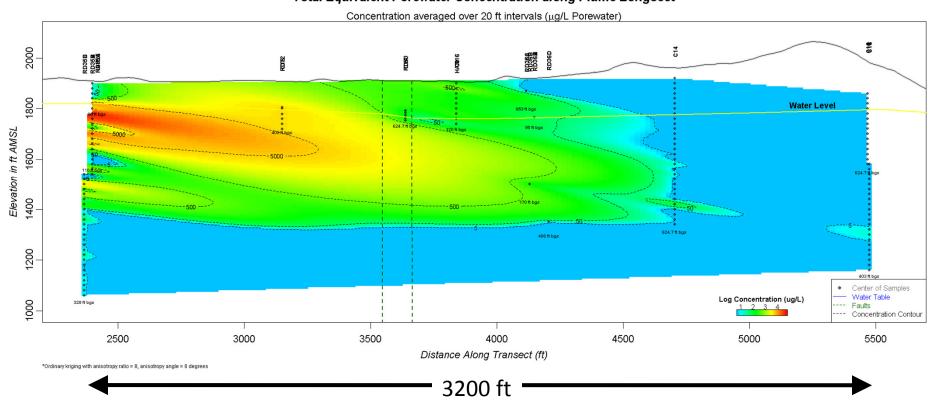
Rock Core and Groundwater Samples

Schematic of TCE Plume at SSFL

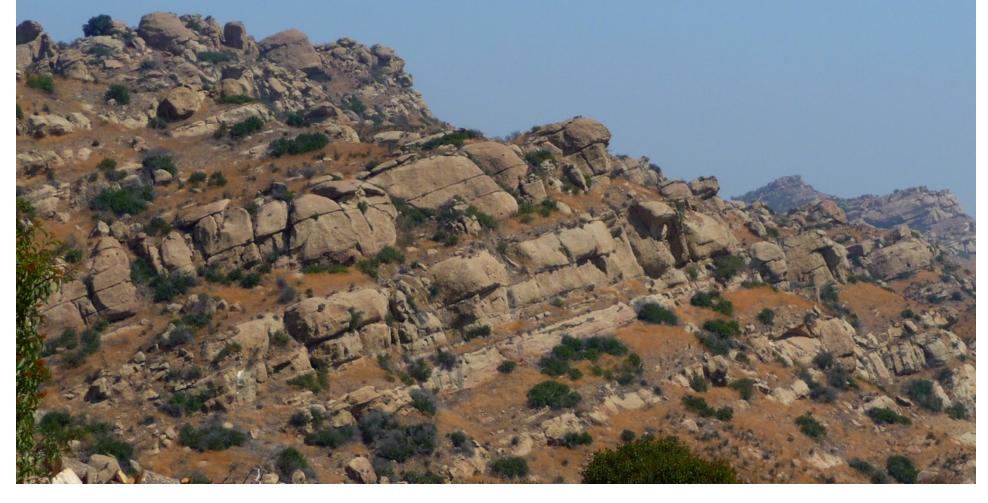


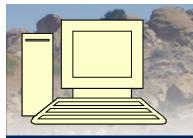
TCE Migration over 60 years

Total Equivalent Porewater Concentration along Plume Longsect

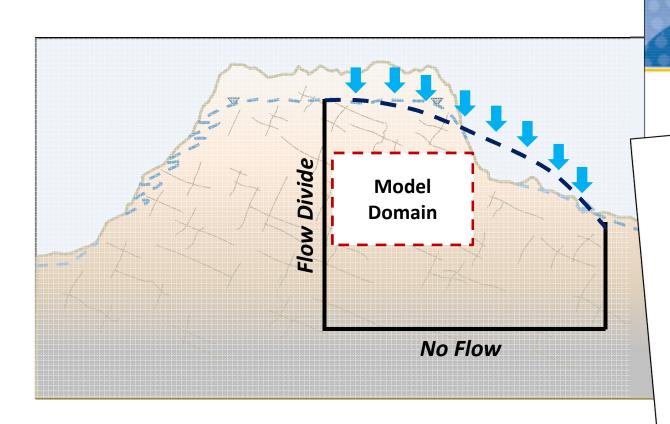








Computer Simulated Plumes



FRACTRAN is a 2D finite element model for simulating steady-state groundwater flow and time-variant contaminant transport in 41 fractured, fully and

WATER RESOURCES RESEARCH, VOL. 28, NO. 2, PAGES 499-514, FEBRUARY

The Laplace Transform Galerkin Technique for Large-Scale Simulation of Mass Transport in Discretely-Fractured Porous

E.A. SUDICKY AND R.G. McLAREN

Waterloo Centre for Groundwater Research, University of Waterloo, Waterloo, Ontario, Canada

Abstract

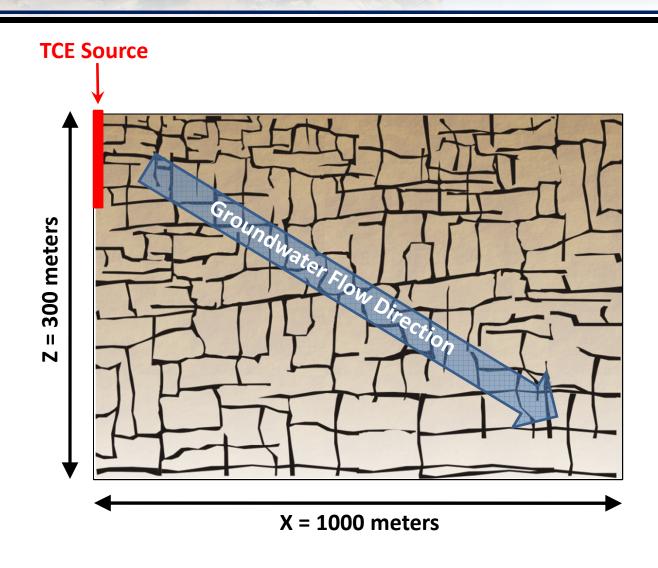
The ability to simulate contaminant migration in large-scale porous formations contaminant according to the processor of the contaminant migration in large-scale porous formations contaminant according to the processor of the contaminant migration and the processor in processor in the season of the discretization transport time-scales in processor in the processor in

It is considered advantageous to isolate hazardous waste substances in a hydrogeological it is considered advantageous to notate nazardous waste substances in a hydrogeological environment composed of low-hydraulic conductivity materials such as clay or intact rock. environment composed or now-nyaranne conductivity materials such as easy or intact rock.

If the host formation is sufficiently tight, then molecular diffusion, a relatively slow process, If the host formation is sufficiently tight, then molecular diffusion, a relatively slow process, responsible the dominant transport mechanism by which contaminants can escape a wester repository and reach either the surface biosphere or an underlying water supply aquifer. A repository and reach either the surface biosphere or an underlying water supply aquiter, a transport regime controlled by diffusion also offers further operational advantages. First, transport regime controlled by diffusion also offers further operational advantages. russ, because diffusion coefficients for many chemicals fall in a relatively narrow range for a variety

¹Copyright 1992 by the American geophysical union Paper number 91WR02560, 0043-1397/91WR-02580805,00 0043.1397/91WR-02560305.00
This document is based on the original text supplied to WRR and as such may vary slightly from the published paper. Rob McLarea, 2008.

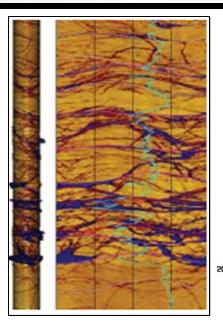
Computer Model Domain



Visual Fracture Observations



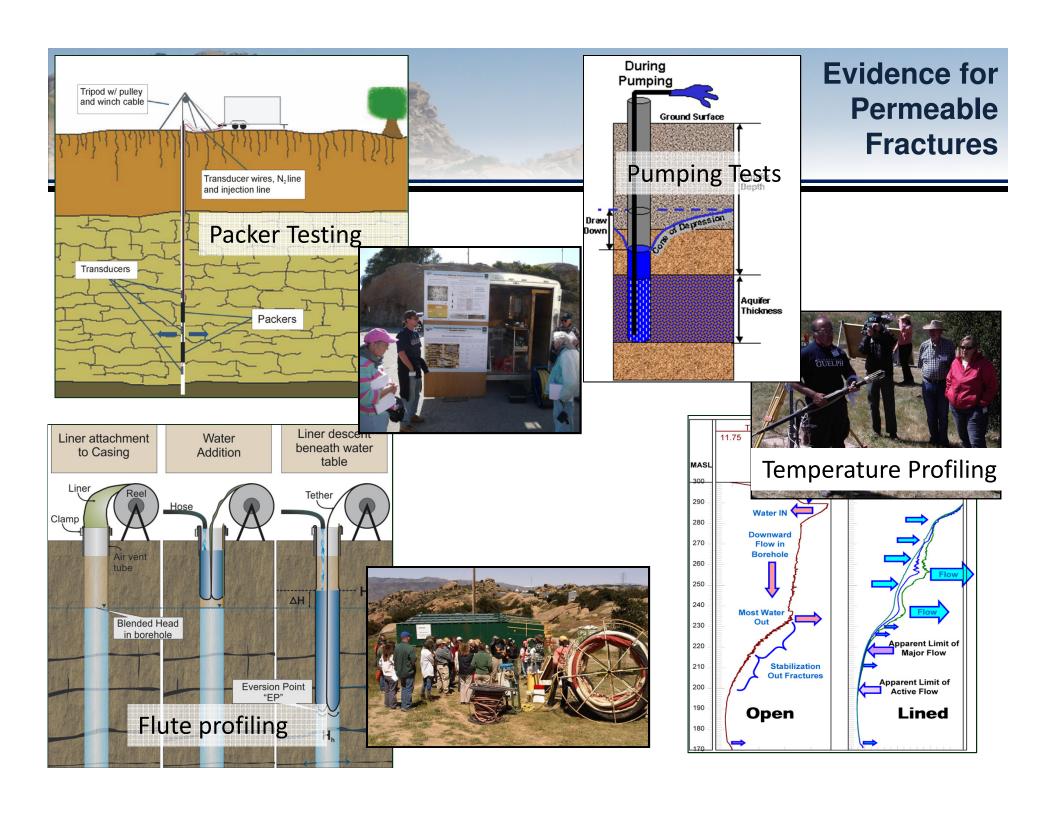




Acoustic Televiewer

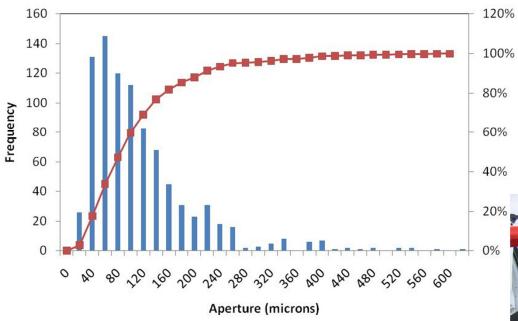








Histogram: FLUTe Liner Test Apertures (C6, C7, C10, C15, C17, RD35C)





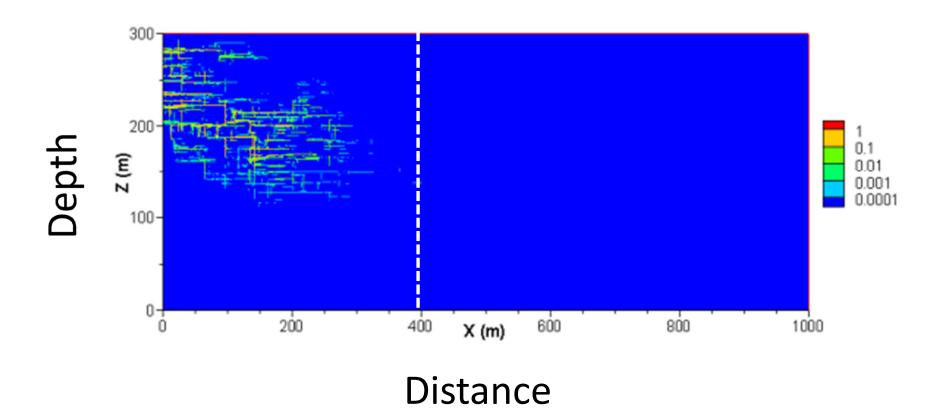
Dense Fracture Network

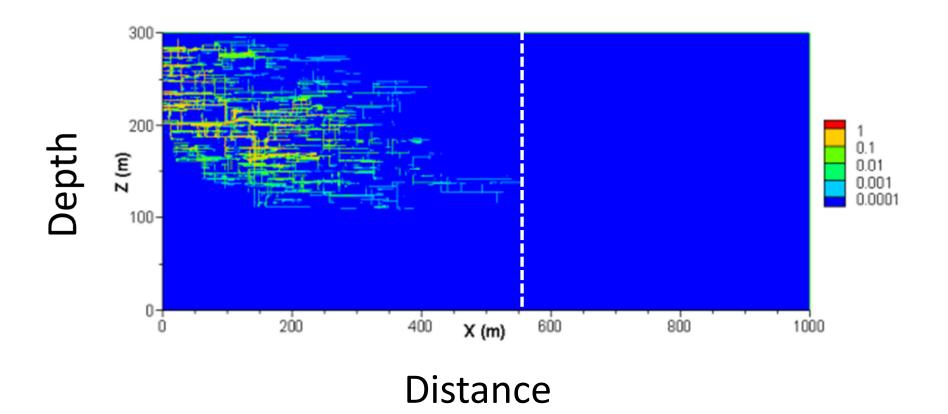
Histogram: Fracture Apertures TCE Source 1200 120% 100% 900 80% 300-600 60% 40% 300 240-20% 00 180-Aperture (microns) Z (m) 120-60-200 400 600 800 1000

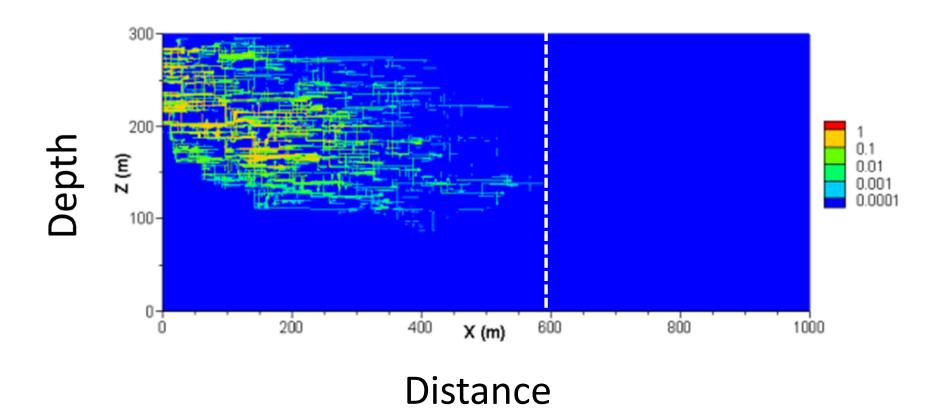
X (m)

Vertical Cross-Section

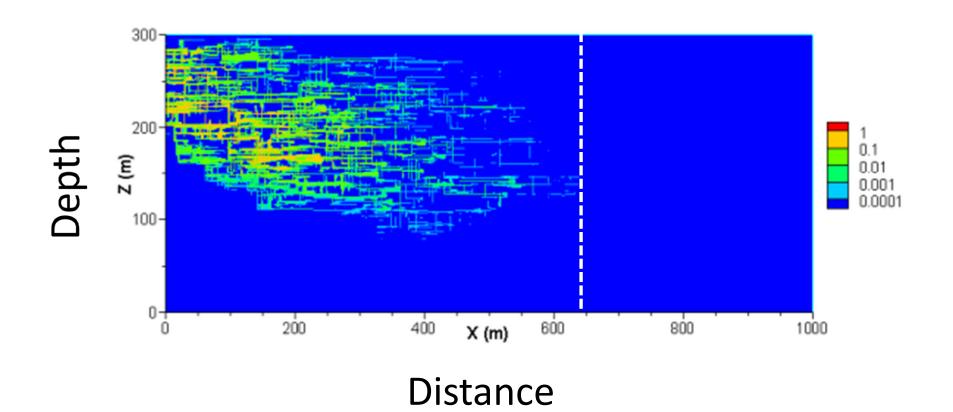
Geometric Mean Fracture Aperture = 100 microns Horizontal Fracture Length Range = 20-100 m

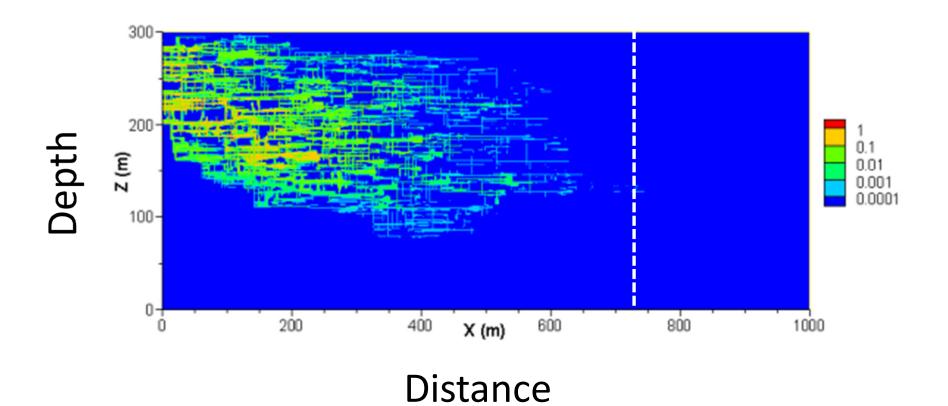


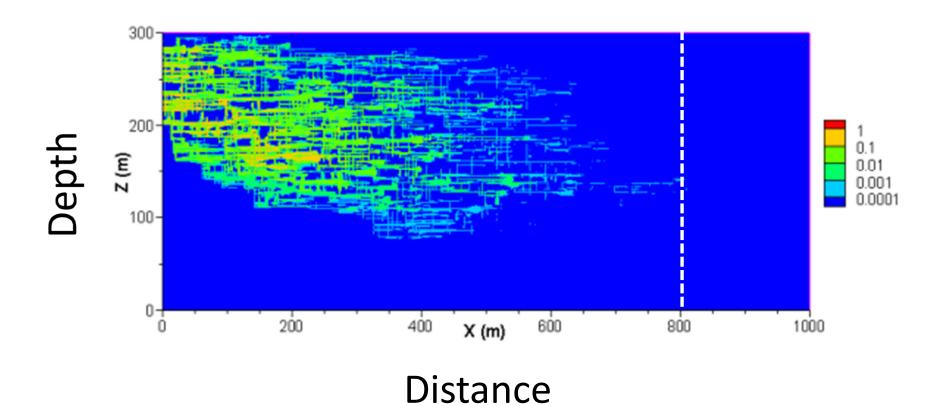




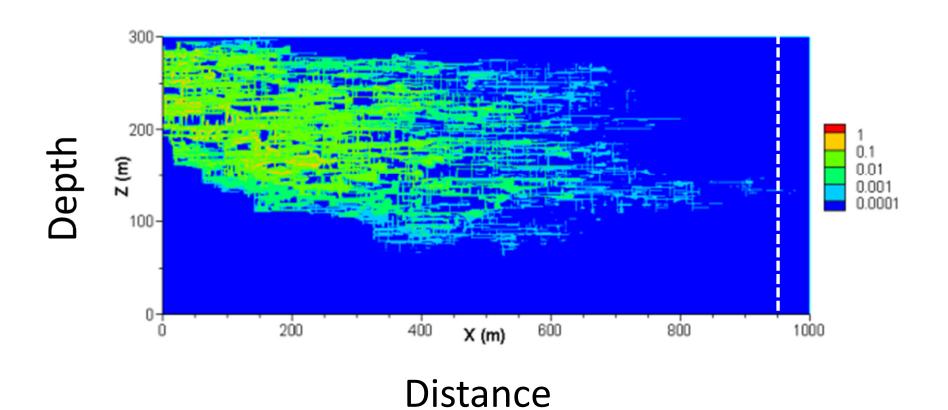


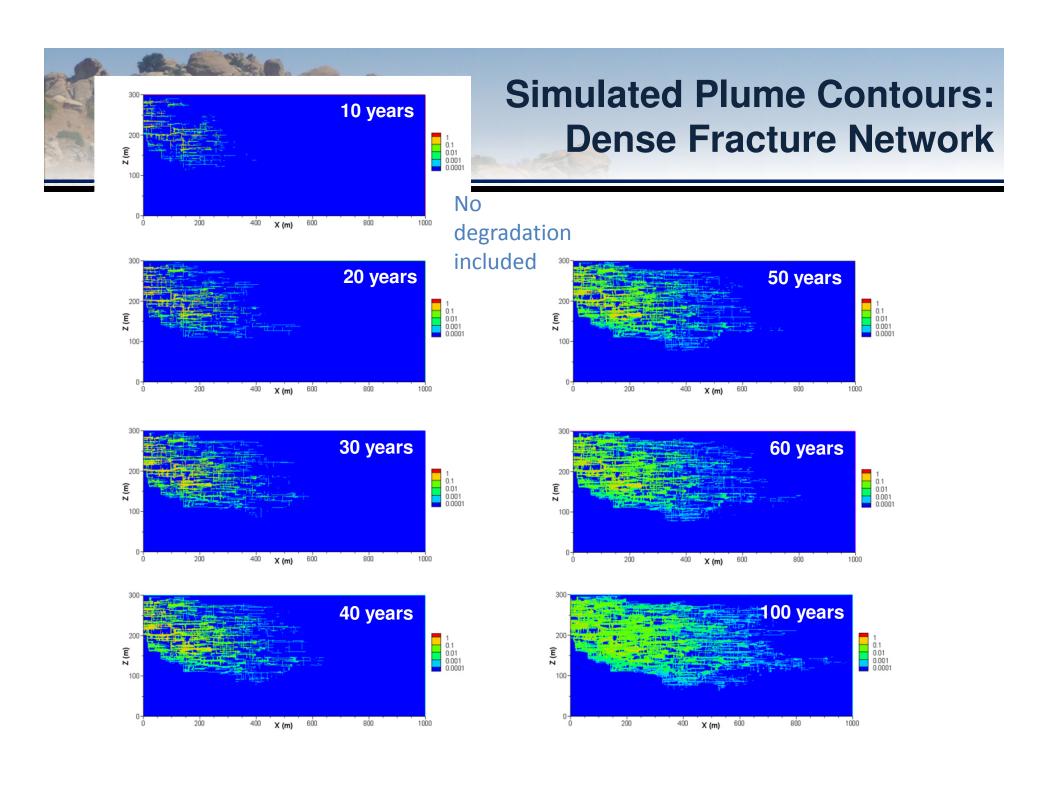










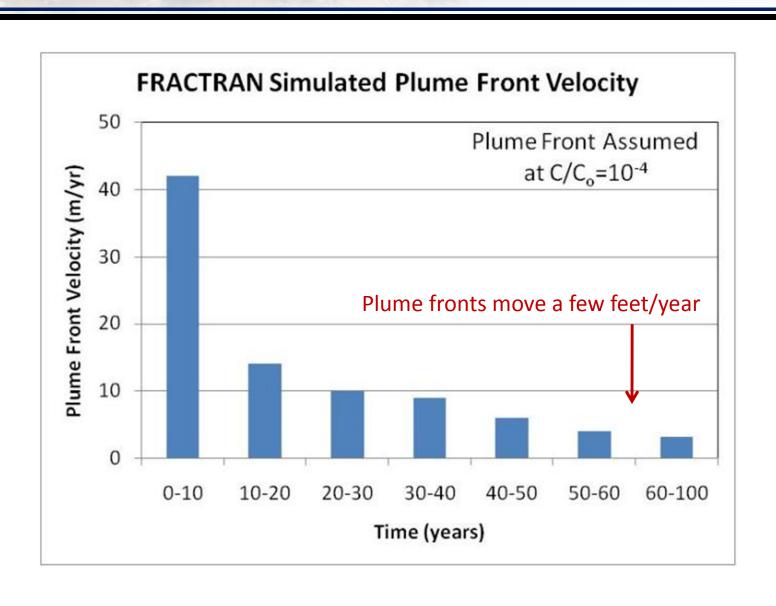




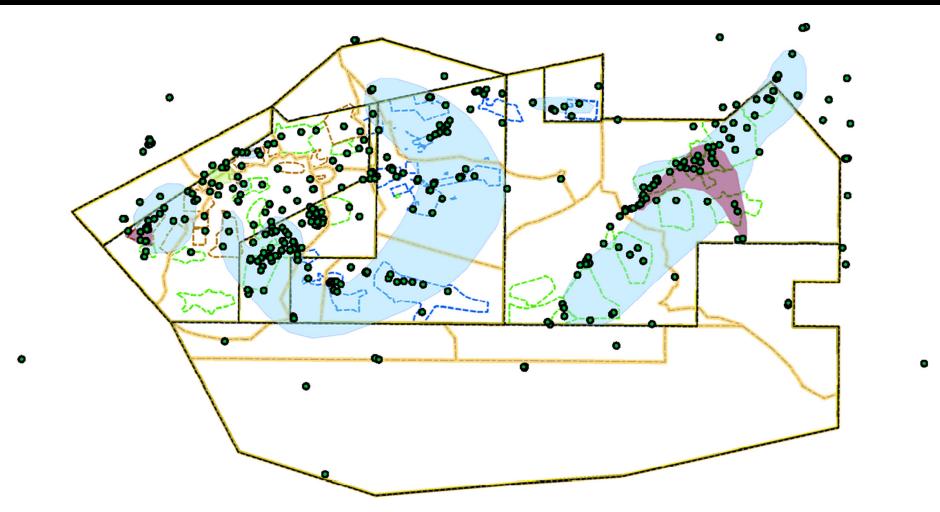
These computer simulations are further evidence for a dense network of interconnected fractures

The influence of matrix diffusion is increased with more fractures

Plume Fronts are Nearly Stationary

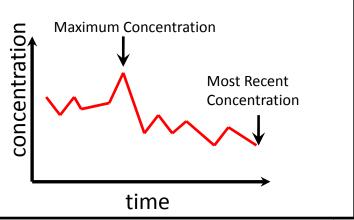


Groundwater Monitoring Network

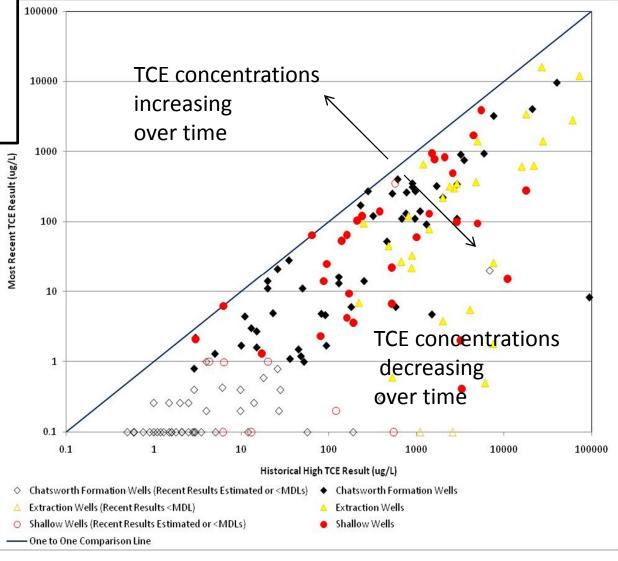


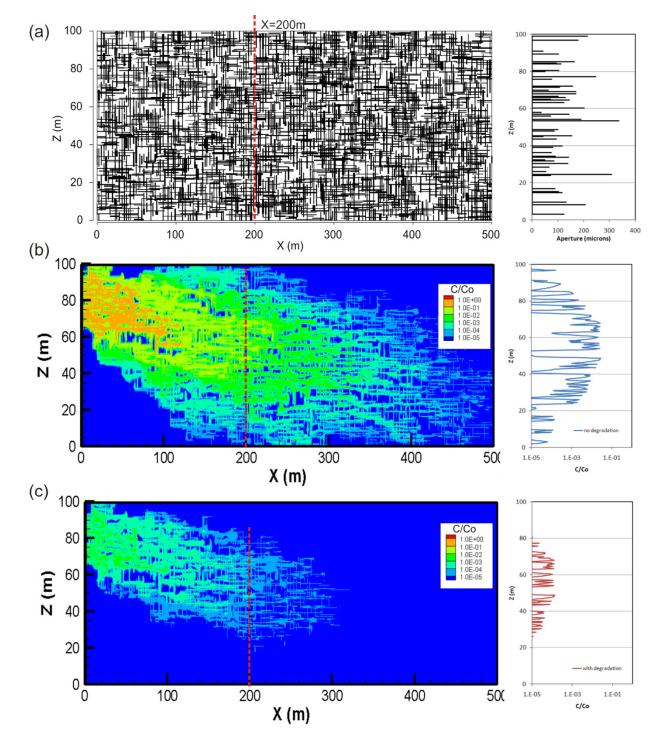
428 wells used to define extent of groundwater contamination

Groundwater concentrations are decreasing



Comparison of most recent results to maximum historical values





TCE Degradation

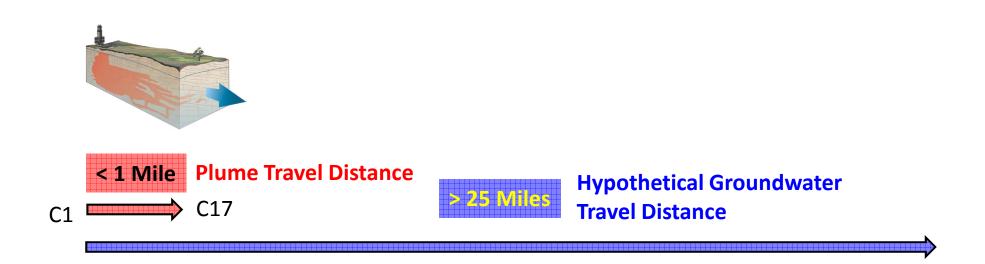
Well-Interconnected Fractures

20 year DNAPL SourceNo Degradation50 years

20 year DNAPL Source
Degradation (5 yr half life)
50 years

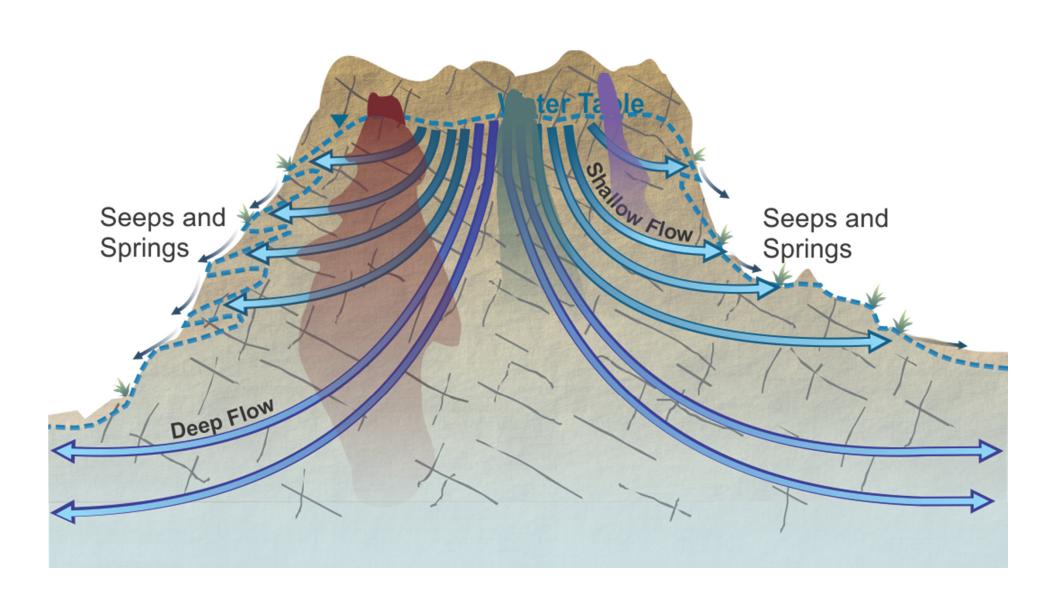


Groundwater plumes are stable and the plume fronts are nearly stationary



Time = 50 years

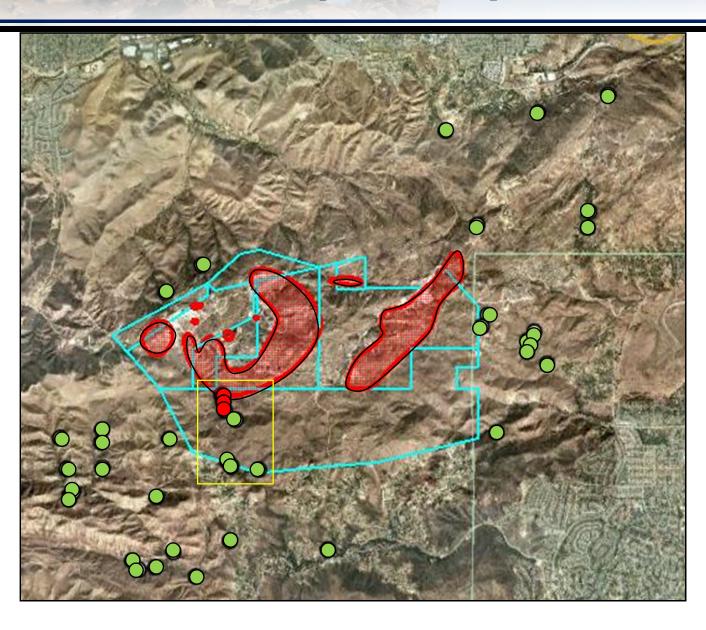
Have plumes arrived at seeps?

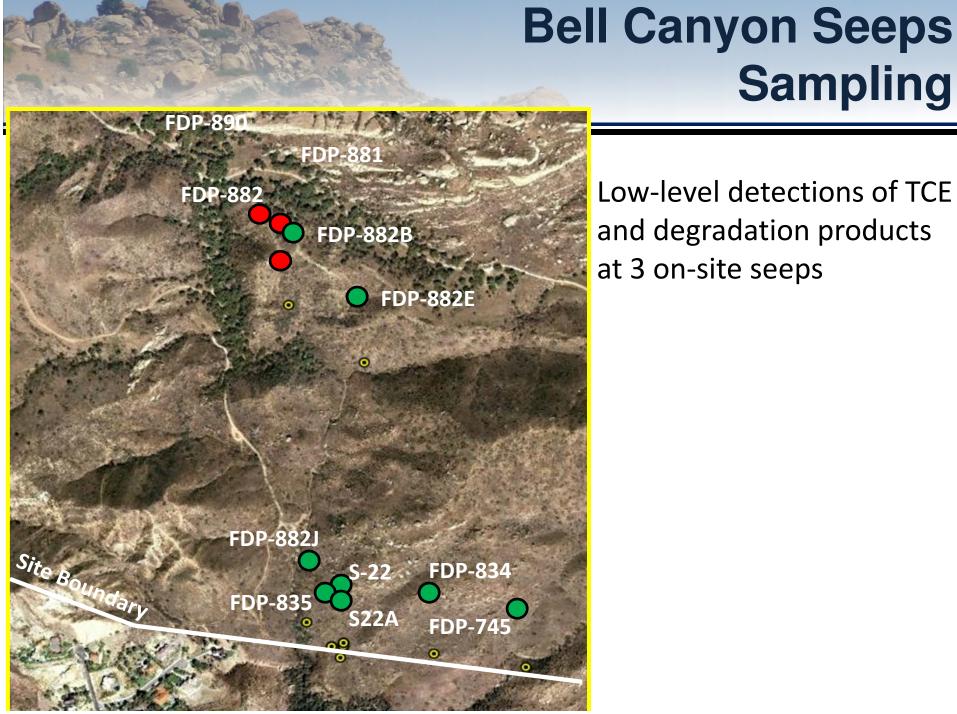




Location of Seeps and Phreatophytes 0000 000 **Legend 900** Seep Ingomar Phreatophyte Image U.S. Geological Survey © 2011 Google 34°13'50:35" N 118°40'43.49"W elev 619 m

44 Seeps Sampled for VOCs



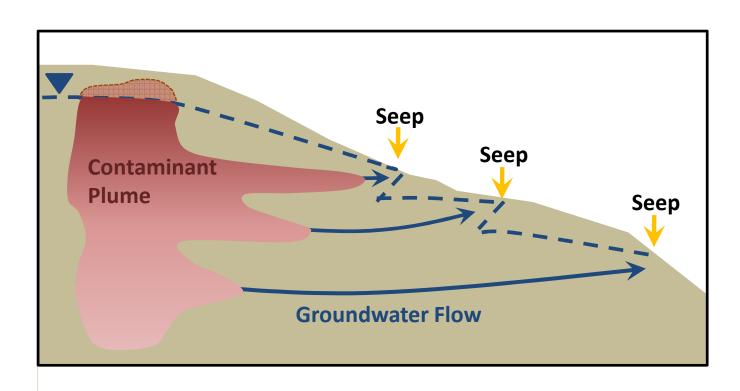


Low-level detections of TCE and degradation products at 3 on-site seeps

Sampling

Key Finding

The plumes have not reached offsite seeps or springs



Processes Influencing Transport and Fate

How Contaminants Move - Transport Processes

- Advection (Flow)
 - Groundwater
 - DNAPL
- Molecular Diffusion

How Contaminants Change - Reaction Processes

- Sorption
 - Adsorption
 - Absorption
- Chemical Reactions
- Biological Reactions

Radioactive Decay

Summary of Key Findings

- Diffusion of contaminants readily occurs in sandstone and shale and is a very important process at SSFL.
- Nearly all the contaminant mass is in the low permeability rock matrix.
- Most of the contamination is found close to where it went into the ground.
- Groundwater plumes are now stable and plume fronts are nearly stationary.
- Contamination has not been found at offsite seeps.

Santa Susana Field Laboratory Located on top of a sandstone mountain (2850 acres)

